The Value of Item-Level RFID in the Supply Chain

Strategic and Operational Aspects

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Abstract

This dissertation investigates the impact of Radio Frequency Identification (RFID) on supply chain management. We develop several economic models that allow for a quantitative evaluation of RFID's value and the strategic implications resulting from its inter-organizational use. Although the ongoing hype about RFID has lead to a high availability of general literature on RFID technology as well as numerous value propositions, the amount of quantitative research about RFID's business value is still small. We address this research gap by investigating three research questions:

1. What economic value can be realized by deploying RFID along the supply chain?

2. What economic incentives have supply chain participants to use RFID cooperatively?

3. What innovative supply chain practices will RFID enable and what is their economic value?

In contrast to earlier research, we constrain our research focus to the determination of the *information and transformation value* of *item-level* RFID in the supply chain of *certain "high-impact" consumer products.*
The first chapter of this dissertation provides the necessary background about RFID's capabilities and expected impact on supply chain management.
The second chapter analyses the strategic consequences of being able to monitor the flow of goods in a supply chain on the item-level. Using a combination of mathematical modeling and numerical simulation we show to what extent the emergence of particular RFID usage equilibria depends on the characteristics of the supply chain.
The third chapter demonstrates the value of RFID-enabled visibility in retail stores if logistical operations are subject to certain kinds of error, in particular misplacements, shrinkage, and transaction errors. We use numerical simulation in order to reveal the effect of the different model parameters on the value of RFID.
The fourth chapter investigates the value of item-level transshipments between retail stores – a practice that could be enabled by the use of item-level RFID. We propose new types of transshipment algorithms of the preventive and the emergency type and evaluate them using numerical simulation.
The fifth chapter deals with the role of logistical information sharing practices in the context of vertical integration strategies. Based on data from the apparel industry we empirically investigate the impact of an increased control of retailing activities exerted by manufacturers and logistical information sharing practices between manufacturers and retailers on the performance of the manufacturers. According to our empirical results advanced logistical information sharing practices are crucial ingredient of successful vertical integration in the apparel industry which underlines the potential of RFID-based systems for monitoring supply chain processes.
Chapter six concludes the dissertation and provides hints for further research on RFID value and strategy.

Keywords:
Radio Frequency Identification (RFID), Supply Chain Management, IT Value

Zusammenfassung

Diese Dissertation beschäftigt sich mit den Auswirkungen der Radiofrequenzidentifikation (RFID) auf das Lieferkettenmanagement. Wir entwickeln mehrere ökonomische Modelle zur quantitativen Evaluation der RFID-Technologie und den strategischen Implikationen ihres unternehmensübergreifenden Einsatzes. Obgleich der anhaltende Rummel um RFID zu einer Flut von allgemeinen Publikationen und zahlreichen nicht belegbaren Nutzenversprechen geführt hat, ist der Umfang der quantitativen Forschung über den ökonomischen Wert von RFID immer noch gering. Wir adressieren diese Forschungslücke, indem wir uns den folgenden Forschungsfragen zuwenden:

1. Welcher ökonomische Wert kann durch den Einsatz von RFID entlang der Lieferkette realisiert werden?

2. Welche ökonomische Anreize haben die Teilnehmer von Lieferketten, RFID gemeinsam zu nutzen?

3. Welche innovativen Praktiken im Bereich des Lieferkettenmanagements wird RFID ermöglichen und was ist der jeweilige Nutzen?

Im Gegensatz zu früheren Untersuchungen konzentrieren wir uns auf die Bestimmung des *Informations- bzw. Transformationsnutzens* von RFID auf der *Einzelteilebene* in der Lieferkette *bestimmter Konsumgüter*.
Das erste Kapitel der Dissertation enthält die notwendigen Hintergründe über die Möglichkeiten der RFID-Technologie und ihr erwarteter Einfluss auf das Lieferkettenmanagement.
Das zweite Kapitel untersucht die strategischen Konsequenzen der Möglichkeit, den Güterfluss in Lieferketten auf der Einzelteilebene zu überwachen. Unter Verwendung einer Kombination von mathematischer Modellierung und numerischer Simulation zeigen wir inwiefern die Entstehung bestimmter RFID-Verwendungsarten von den Eigenschaften der Lieferkette abhängt.
Im dritten Kapitel veranschaulichen wir den Wert der durch RFID ermöglichten Sichtbarkeit von Produkten in Einzelhandelsfilialen wenn die logistischen Prozesse durch verschiedene Fehlerarten, speziell Fehlplatzierungen, Schwund und Transaktionsfehler, beeinflusst werden. Wir verwenden numerische Methoden, um den Einfluss der verschiedenen Parameter des Modells auf den Wert von RFID zu untersuchen.
Im vierten Kapitel quantifizieren wir den Wert von Bestandsreallokationen zwischen Einzelhandelsfilialen – eine Praktik, die durch den Einsatz von RFID auf der Einzelteilebene ermöglicht werden könnte. Wir schlagen neue Typen von Bestandsreallokationsalgorithmen des präventiven und des Notfall-Typus vor und evaluieren diese im Rahmen einer numerischen Simulation.
Das fünfte Kapitel beschäftigt sich mit der Rolle des Austauschs von Logistikinformationen im Kontext der Vorwärtsintegration. Basierend auf Daten aus der Bekleidungsbranche untersuchen wir die Auswirkungen erhöhter Kontrolle von Verkaufsaktivitäten durch die Hersteller und eines intensivierten Informationsaustauschs zwischen Bekleidungsherstellern und -händlern auf die Leistungsfähigkeit der Hersteller. Unseren Ergebnissen zufolge ist der erweiterte Informationsaustausch ein entscheidender Bestandteil erfolgreicher Vorwärtsintegration in der Bekleidungsbranche, was das Potential der RFID-gestützten Überwachung der Lieferkette unterstreicht.
Kapitel sechs beschließt die Dissertation und bietet Hinweise für weitere Forschungsvorhaben im Bereich des Wertes von RFID und entsprechender Einführungsstrategien an.

Schlagwörter:
Radiofrequenzidentifikation (RFID), Lieferkettenmanagement, Wertbeitrag von Informationstechnologie

Contents

Chapter 1

Introduction

This dissertation investigates the impact of Radio Frequency Identification (RFID) on supply chain management. RFID allows for the contactless identification of objects. A basic RFID system consists of three components: the RFID transponders or tags, the RFID reader device, and a backend IT system. The RFID transponder consists of a silicon chip that can store data and a miniaturized antenna used for communication attached to the chip. RFID transponders can communicate with RFID readers using radio waves. RFID systems can differ with respect to the bandwidth they use, the storage capacity of the tags, and the power source of the tags. RFID tags without battery are referred to as "passive". Passive transponders are "woken up" by the readers radio waves carrying an activation signal. The power of the radio signal suffices for enabling the transponder to send a short response, e.g. its unique identification number. In contrast to that, "active" RFID transponders have their own energy supply. On the one hand this allows for more freedom in protocol design because these transponders can initiate communication themselves. On the other hand it has technical advantages since the signal of the transponders is more powerful and thus enables communication over longer distances. This dissertation only deals with passive RFID technology whose importance in logistics and supply chain management applications is steadily increasing.

Although the difference between passive RFID and the bar code may not appear significant at first glance, RFID-based object identification has a number of unique properties. Gaukler [2005] mentions the following:

1. Contactless and remote interrogation

2. No line of sight required

3. Multiple parallel reads possible

4. Individual items instead of an item class can be identified

The first three properties essentially make item counting very cheap. Scanning products using RFID is quicker and involves far less human intervention than scanning bar codes. Property four allows for a number of completely new applications based on RFID-enabled product tracking and tracing. For instance, the RFID-based tracking and tracing of products can improve the efficiency of product recalls, the management of returns and warranties, or for preventing product theft and counterfeit. It can also improve operational supply chain management practices. Such practices include the ones treated in this dissertation, e.g. the detection and prevention of errors in delivery processes (cf. Chapter 2), the optimization of order and replenishment processes (cf. Chapter 3), the use of innovative operational practices that depend on high inventory visibility and process efficiency (cf. Chapter 4), and effective information sharing practices which represent a crucial ingredient of vertical integration strategies (cf. Chapter 5).

Using reflected radio energy for communication is not a new concept. In fact, it dates back to the origin of radar technology. For example, the "Identify Friend or Foe" (IFF) transponder introduced by the British Air Force in the Second World War used the exact same technical principle. The first commercial application of RFID, electronic article surveillance, was developed by companies such as Kongo, Sensormatic, and Checkpoint in the late 1960s (Chawla and Ha [2007]). However, the commercialization of RFID applications only picked up in the 1980s and 1990s. In the United States, solution providers started to integrate RFID in transportation and personnel access systems. In Europe, RFID became popular in the area of animal tracking and toll collection.

Standardization activities regarding RFID technology started in the 1990s. Most of them were conducted by the International Standardization Organization (ISO) and the International Electrotechnical Commission (IEC). The first RFID related standards referred to animal tracking (ISO-11784 and ISO-11785) and applications of contactless proximity cards (ISO-14443). The commercial interest in RFID grew rapidly in the second half of the 1990s. A milestone was the standardization of RFID as a data carrier by the Article Number Association (ANA) and the European Article Numbering (EAN) groups in 1996. In 1999, EAN International based in Europe and the Uniform Code Council (UCC) based in the United States, now both known under the name GS1, designated a UHF frequency band for RFID and established the

Auto-ID Center at the Massachusetts Institute of Technology. The Auto-ID Center was commissioned to develop a global RFID standard for product identification called the Electronic Product Code (EPC). Later the original Auto-ID Center evolved into the Auto-ID Labs and the industry consortium EPCglobal which now have branches in many parts of the world. EPCglobal is a nonprofit organization installed by the UCC and EAN International and charged with pursuing the commercialization of the EPC and related technology standards.

Nowadays, RFID is perceived as one of the most promising information technologies. Lee [2007] states that "after the Internet, RFID technologies have become the most talked about innovation that is supposed to revolutionize the ways we conduct businesses". According to Chawla and Ha [2007] recent advances in silicon technology have made passive RFID tags relatively cheap and reliable. Although the use of RFID in liquid and metal environment remains difficult, many promising applications in the supply chain have become technically feasible (cf. Gaukler and Seifert [2007]). Major companies from the vendor as well as the user side have been relentlessly promoting the technology since several years. Examples for the former include major business software vendors such as SAP, IBM, and Oracle. A major landmark on the user side was the initial announcement of Wal-Mart to mandate RFID for its suppliers in 2003 (cf. Mah [2008]). The German Metro group, another major player in the retail sector, has also required their suppliers to tag pallets and cases (cf. Anonymous [2007]). In their so-called Future Stores located in Rheinberg and Tönisvorst they even investigate the potential of item level RFID: it is used on several items to drive both in-store and outside stock replenishment (cf. Anonymous [2009]). Moreover, a self check-out system for RFID tagged products has been implemented in these stores.

Recent industry reports show that RFID adoption increases steadily (cf. e.g. IDTechEx [2007], GS1/LogicaCMG [2007]). However, the overall adoption rates are still lagging behind expectations. In particular the use of RFID for monitoring supply chain processes and on the sales floor has been unexpectedly low to date (cf. e.g. Schmitt and Michahelles [2008]). Back in 2006 the biggest share of RFID transponders produced worldwide, namely 556 million, was still purchased for established applications such as "smart" cards, keys, passports and tickets IDTechEx [2007]. Only 388 million of the transponders that were sold in 2006 were used for the purpose of identifying goods including drugs, tools, books, apparel and other consumer products (153 million) and logistical units like packages, cases, and pallets (235 million).

The use of RFID transponders for closed loop applications like smart cards is fundamentally different from open loop product tracking in the supply chain. In the former setting, each RFID tag can be repeatedly used in the same process and its lifetime can thus be maximized. In the latter application, RFID tags may be used at several read points in the supply chain but their usage time usually ends when the corresponding products are sold to the end customer. The cost of RFID transponders in closed loop settings can thus be justified more easily due to their high utilization.

Due to the difficulty of proving benefits that clearly justify the RFID transponder cost, item-level tagging in the retail supply chain has so far not gained significant momentum. Apart from a number of small scale pilots (cf. e.g. Wessel [2007], Gaudin [2008]), no item-level RFID implementations have been reported so far. However, this situation could change due to the dynamics of the tagging cost and benefit expectations. If only a handful consumer good manufacturers starts to tag their products on the item level, the demand for tags will significantly increase. The resulting drop of the per unit tag prices would make RFID usage attractive for other companies. If those companies also attach tags to their products the demand for passive transponders would increase even further. Ideally, this RFID diffusion process would continue until RFID's economic potential has been fully realized. Apart from locking the tag price on a relatively high level, RFID's slow adoption impedes the discovery of RFID's benefits in the supply chain and beyond as well as its technological advancement: although the baseline technology has reached a high level of reliability, only its stepwise integration into applications and business processes will reveal unforeseeable benefits and technical challenges.

RFID-related research has so far concentrated on two broad aspects, namely the quantification of its benefits and its technological advancement (in particular the development of RFID and EPC-related standards). In practice both aspects are highly relevant. The recent hype around RFID has attracted many companies from different industries that are interested in its value. Mandates from major retailing companies have further increased the pressure to identify and exploit the benefits of the technology. More knowledge about RFID's value and the provision of accurate methods for estimating its costs and benefits support companies in their decision making and help them to realize RFID's potential in a systematic manner. The development of prototypical system components and standards eases RFID's technological integration as soon as RFID adoption gathers pace.

1.1 Research Focus and Contribution

The central theme of this dissertation is the economic value of item-level RFID in the supply chain and the strategic implications of its use. In particular, we provide answers to the following general research questions.

1. What economic value can be realized by deploying RFID along the supply chain?

2. What economic incentives have supply chain participants to use RFID cooperatively?

3. What innovative supply chain practices will RFID enable and what is their economic value?

Instead of treating these research questions in a general manner, we deliberately constrain our research focus to the determination of the *information value* of *item-level* RFID in the supply chain of *certain "high-impact" consumer products*. We justify this topical containment in the following.

1.1.1 Information/Transformation Value versus Automation Value of RFID

RFID benefits can be subdivided into the following categories:

1. Labor and time saving due to process acceleration (referred to as the *value of automation*)

2. Benefits from higher visibility and data quality (referred to as the *value of information*)

3. Benefits resulting from newly introduced business practice enabled by RFID (referred to as the *value of transformation*).

This value breakdown has been introduced by Mooney et al. [1996] and has already been applied to RFID by several authors, e.g. Thiesse et al. [2009] and Baars et al. [2009]. In practice, many RFID profitability calculations are to a large degree based on benefits belonging to the first category, i.e. the value of automation. On the one hand, these benefits can be computed with relative ease provided the corresponding processes have been analyzed. On the other hand, they are expected to directly follow from RFID usage which increases the perceived certainty of returns - a highly important criterion for decision makers in industry sectors with relatively low profit margins such as logistics and retail.

The value of information is generally more emphasized by the academic literature (cf. e.g. Lee and Özer [2007]) although it is also increasingly acknowledged by technology analysts and consultancies (cf. e.g. Grocery Manufacturers of America/A.T.Kearney/IBM [2007], Kurt Salomon Associates [2005]). On the one hand, RFID allows for collecting more timely and accurate data on the state of processes and the location of assets. Typical supply chain execution errors such as mistakes in the picking process can be detected instantaneously. Furthermore, RFID allows for pinpointing locations in the supply chain where shrinkage and misplacements occurs. This information can be used to take adequate countermeasures against product loss and to improve inventory control along the supply chain – at the manufacturer's warehouse as well as in the retailer's distribution center and stores. Improved inventory control can reduce out-of-stock situations and the amount of safety stock. Conservative estimates of product loss in the retail supply chain range in the region around 2% of sales (cf. e.g. Alexander et al. [2002]). The worldwide out of stock rate in retail stores is about 8% (Gruen et al. [2002]). Although only a part of retail stock-outs actually result in lost sales, the loss of revenue due low product availability can be substantial in practice (Gruen et al. [2002], Roland Berger Strategy Consultants [2003]).
On the other hand, the use of RFID can enable process transformation, i.e. the reengineering of existing business processes and supply chain practices in response to the insight gained from the analysis of RFID data or the use of RFID data as an enabler of completely new processes and/or practices. Benefits in the information value and process transformation category are harder to estimate since they often necessitate a model of supply chain control and how this control can be improved by information extracted from RFID data (cf. Lee and Özer [2007]).

Both the value of automation and information have to be taken into account in order to provide accurate RFID profitability estimates. Placing the focus of benefit assessment on automation benefits rather than considering the whole range of benefits even if it implies more effort can have disadvantages. It may leave the realization of information and transformation benefits to competitors and even threaten the market position of a company. A recent study of A.T. Kearney and IBM conducted for the Grocery Manufacturers of America estimates the value of information at least as high for most types of products as the value of automation (Grocery Manufacturers of America/A.T.Kearney/IBM [2007]). Since the estimation of RFID's information and transformation value necessitates more sophisticated tools and analyses, we believe that the contribution of research in this field can be higher than in the area of automation benefits.

1.1.2 Item versus Case/Pallet-level RFID Tagging

We have chosen to focus on the *item-level* RFID tagging of *consumer products* due to the following reasons. First of all, the use of RFID for tracking cases, containers and boxes that are used within supply chain facilities is already common place. This is mainly due to the fact that the return on RFID investment in closed-loop settings is usually higher due to the increased utilization of tags. The item-level RFID tagging of single products on the other hand is still a highly innovative practice. Only a small number of organizations have started to evaluate item-level RFID using pilot studies, in particular apparel retailers (cf. Goebel et al. [2009c], Gaudin [2008]). Secondly, the value of using case/pallet-level tags in closed and open-loop settings is already relatively well known in practice. This is primarily due to the RFID mandates issued by Wal-Mart and other major retail companies. In order to avoid sunk costs, the concerned manufacturers have been intensively searching for benefits that can be obtained from case- and pallet-level tagging in recent years (cf. Grocery Manufacturers of America/A.T.Kearney/IBM [2007]). Although case/pallet-level RFID tagging has probably not been adopted wherever it makes economic sense, its economic relevance is rather limited compared to the expected impact of item-level RFID due to the following reasons: the use of RFID tags attached to logistical units is restricted to a foreseeable number of applications in the supply chain, in particular applications that enable the frictionless documentation of deliveries. Item-level RFID on the other hand holds more potential because it allows for identifying single object instances and conduct efficient product counts wherever the derived information may be useful.

Thirdly, the passage from case/pallet-level tagging to item-level tagging is expected to have far-reaching consequences not only for single companies but for the economy and society as a whole. Its value and risks may not be limited to the supply chain but may also extend to the consumer side. On the one hand, the integration of RFID into consumer products could enable many promising services, e.g. the "intelligent" fridge that checks the storage life of food products and automatically orders products if necessary. Or the "intelligent" washing machine which refuses to wash light and dark clothes at the same time. Many more applications are imaginable if one considers the possibility of linking information about the location of items to previously data from heterogeneous information sources, e.g. the World Wide Web (WWW). In fact, the prospect of these possibilities has lead to an entirely new field of research, the so-called "Internet of Things".

1.1.3 RFID Tagging of High- versus Low-Impact Products

Intuition tells us that it will not be equally profitable to attach passive RFID transponders to every product. The automation, information, and transformation benefits derived from being able to track and trace product movement on the item-level will on the contrary be highly dependent on the respective product characteristics. The questions is what are these characteristics and how significantly do they influence the costs and benefits derived from RFID usage. As far as the value of automation is concerned companies that have already maximized the efficiency of their operational processes in distribution centers and retail stores will benefit relatively less from the adoption of RFID than companies with less efficient processes. The time savings that can be realized by replacing automatic bar code scanners by RFID-based solutions, for instance, are rather small in most cases. If RFID is used to collect more detailed and/or accurate data and the corresponding information or transformation value is realized, the value of RFID depends on at least two factors: The value of the product and the significance of process inefficiencies that can be potentially eliminated by the use of RFID. The value of the product plays a twofold role. On the one hand high value products yield a higher per unit revenue than low value products and thus the ROI of each RFID transponder is higher if RFID-derived process improvements lead to fewer out-of-stock situations in retail. On the other hand, the shrinkage of high value products causes higher losses. The significance of process inefficiencies has a straightforward positive impact on the value of RFID because the more errors can be detected and prevented by the use of RFID the more it helps to improve efficiency. Consequently the highest RFID value can be realized in supply chains procuring products that are both valuable and prone to shrinkage and other process inefficiencies. In accordance with Kearney [2003] we term such products "high-impact" products throughout this dissertation. Table 1.1 provides some examples of high- and low-impact type of products. Considering that item-level RFID tagging will most likely start in the "high-impact" product category, we focus on this kind of product. In this dissertation only the benefits of RFID in supply chain management are considered. However, the potential for after sale services that can be supported using item-level RFID is also higher for high-value products. On the one hand, the chances that a consumer wants to know more about the use of a new drug or the working of an electronic appliance are high com-

High-impact products	Low-impact products
OTC drugs	Dry grocery
Video games	Perishables
Electronics	Beverages
Apparel	Frozen foods
Cosmetics	Soaps and cleaners

Table 1.1: Examples of high- and low-impact products (adapted from Kearney [2003])

pared to the informational needs regarding products whose properties do not significantly change over time, such as detergents or basic food products. On the other hand, higher value and longer average usage times imply a higher demand for other product-related services, in particular product returns and repairs.
Most of the publicly available industry white papers and consultant reports point to the issue that product characteristics have a significant influence on the value of RFID (e.g. Kearney [2003] and Grocery Manufacturers of America/A.T.Kearney/IBM [2007]). Furthermore, recent analyses of the RFID market suggest that it will grow as a result of increasing item-level tagging of high value products such as apparel (cf. GS1/LogicaCMG [2007]). This prediction corresponds with the above hypotheses since it can be expected that the biggest benefit potentials will be targeted first.

1.2 Outline

In Chapter 2 we investigate the impact of the non-cooperative and cooperative use of item-level RFID on the profits of a prototypical manufacturer and retailer. Using formal representations of the profits of the supply chain participants in different RFID usage scenarios, we show that the use of RFID leads to different kinds of externalities. The existence of these externalities may result in strategic behavior of the supply chain participants. Using basic tools from game theory, we demonstrate how the strategies of the involved stakeholders are affected by the model parameters and determine strategic equilibria. Based on numerical results we are able to show in which situations the cooperative use of item-level RFID is more likely than its non-cooperative use.

In Chapter 3 we investigate the impact of item-level RFID on the profit of retail stores. Using numerical simulation we are able to show the value of RFID data for inventory control. Based on the results of an extensive sensitivity analysis and previous work by other authors we provide insights into the complex trade-offs that have to be considered in order to provide more accurate RFID benefit estimates in retail environments.

In Chapter 4 we investigate the benefits of item-level transshipments of product stock between retail outlets. This operational supply chain practice relies on high inventory visibility and execution efficiency and may therefore be enabled by item-level RFID. We introduce a corresponding supply chain model and describe an effective algorithm that determines transshipment quantities based on the inventory levels at several retail outlets. The results of a simulation study show that transshipments can lead to significant cost savings, even after the entire tagging cost has been subtracted.

In Chapter 5 we investigate the impact of vertical integration and information sharing between manufacturers and retailers on the performance of the manufacturers in the apparel industry. Our empirical results suggest that exerting more control over the retail stage of the supply chain provides benefits to apparel manufacturers and that intensive information sharing with the retailers is a crucial ingredient. The emergence of different concepts for vertical control in the apparel supply chain, e.g. franchises, shop-in-shop solutions and concessions, emphasizes the importance of vertical control. Our results shows that these concepts can only be successful if information sharing practices keep pace with their implementation. Cross-company information systems based on item-level RFID that enable logistical data sharing among manufacturers and retailers can play an important enabler role in this context.

Chapter 2

Strategic Aspects of Cross-Company RFID Usage

2.1 Introduction

The core vision of the industry consortium EPCglobal is the use of standardized item-level RFID along the supply chain of consumer products (EPCglobal [2007b]). In particular, they propose the standardized Electronic Product Code (EPC) that can be used as unique product identifier. To date, however, the manufacturers and retailers of consumer goods have not reached a consensus on whether it is profitable to integrate item-level RFID into their business processes. The cross-company use of item-level RFID involves a high level of coordination, both economically and technically. On the one hand the different companies taking part in a typical consumer goods supply chain perceive their respective costs and benefits differently. Usually the manufacturers see little benefit in tagging their products on the item level while retailers are expected to realize most of the benefits (cf. e.g. Kambil and Brooks [2002]). The uncertainty about costs and benefits as well as the unequal distribution of profits in cross-company RFID rollouts represents a crucial adoption barrier (cf. Goebel et al. [2009b]). On the other hand, the cross-company use of RFID implies that manufacturers and retailers use the same RFID transponders which calls for standardization of the corresponding hardware and product identification codes. Although RFID standardization efforts have been very successful, the slow adoption of the developed standards leads to a lack of real world experiences which in turn complicates purposeful advancements of the standards.

RFID advocates still claim that the use of item level RFID along the supply chain will eventually create value for all supply chain participants (cf. Chappell et al. [2003b]). It is expected not only to reduce labor cost and speed up tedious documentation processes, but also to provide timely and accurate information that can be valuable for improving supply chain management. Furthermore, the RFID based collection of product traces makes other promising applications, such as electronic counterfeit prevention, economically feasible (cf. Staake et al. [2005]). We describe some of the frequently cited benefits of cross-company RFID in more detail below.

According to the popular SCOR model (cf. Supply Chain Council [2008]), supply chain management encompasses the following activities:

1. Planning
2. Souring raw materials
3. Making the product
4. Delivering the product
5. Managing product returns

Each of these general activities can be represented by a collection of processes. These processes can be coarsely categorized according to their general function. The SCOR model distinguishes the following three general process categories:

1. Planning processes
2. Execution processes
3. Enabling processes

Supply chain planning processes are designed in a way such that the expected consumer demand is satisfied in the most efficient way. Supply chain execution processes assure that the plans determined by the planning processes are effectively implemented, e.g. that ordered products arrive at the customer at the right time and in the planned quantity. Enabling processes refer to the management of information that is required by the planning and execution processes. The overall impact of supply chain management on the performance of a supply chain depends on how well the different activities and processes are coordinated and aligned in order to increase competitiveness. The coordination of supply chain planning and execution thus plays a crucial role. If the supply chain plan is not effectively executed, the participating

organizations are likely to miss their performance goal. Thus, everything that helps to close the gap between supply chain planning and execution is likely to increase supply chain performance. This coordination of plans and actions is the purpose of the enabling processes. These processes are supposed to assure that planning information reaches the responsible decision makers and that the execution of supply chain processes can be monitored and controlled. Against this background, RFID can be regarded as a technology that supports the enabling processes in a supply chain by providing more timely and accurate information about the current state of products in the supply chain. It can help to close the gap between supply chain planning and execution which is a precondition for high supply chain performance.
On the one hand, the availability of timely and accurate information about the execution of supply chain processes allows managers to take immediate action if something goes wrong. In food supply chains, for example, a higher degree of supply chain visibility can for instance support efforts to safeguard product freshness (cf. e.g. Shim et al. [2007]). Based on real time tracking data, the responsible supply chain manager can be notified whenever a process step takes longer than usual. This knowledge can in turn be used to take immediate and directed action to reduce the total amount of time that the corresponding food products spend in the supply channel until they are delivered to consumers. RFID-based solutions for the real time control of time-sensitive processes have for instance been proposed by Goebel and Tribowski [2008]. The time and cost of such process improvements naturally depends on the availability and expense of the measures that can be taken to compensate delays.
On the other hand, the existence of detailed historic information about the outcome of supply chain execution processes can help supply chain managers to reveal constant or seasonal departures from the plan and identify the reasons of their existence. This knowledge in turn can provide the basis for long term improvements of supply chain execution.

Apart from its potential in the context of supply chain panning and execution, RFID data can also help to reduce the cost resulting from quality problems and product counterfeiting. Since automatic item-level identification enables stake holders along the supply chain to match the current location of a product with the time and place of its production, it can serve to identify defective products long after they have been produced. Regarding the high cost of traditional product recalls, this can lead to significant cost savings (cf. e.g. Chappell et al. [2003a]). Regarding the detection of product counterfeit a number of promising methods have been proposed in recent years (cf. e.g. Al-Kassab et al. [2008]). They usually rely on machine learning techniques that allow for the identification of unusual movement patterns based on "usual" patterns inferred from large amounts of historic data.

The use of RFID standards can have a direct impact on the RFID adoption decision of organizations since it makes the purchase and integration of RFID hard and software less expensive. On the one hand, the use of standardized RFID solutions along a supply chain allows for using the same tags repeatedly. If transponders are used in the distribution center operated by the manufacturer of a product, they can also be used in the stores of the retailer provided that the readers and numbering schemes are compatible. If the total RFID tagging cost is shared among the supply chain participants, this leads to cost savings for all of them. On the other hand, RFID standards increase the competition of RFID hard and software vendors. If all available RFID readers implement the same communication protocols and are designed to read the same RFID transponders, the companies using them are less dependent on a particular RFID vendor. This in turn reduces switching costs and encourages the companies that already use RFID to continuously search for alternative hardware vendors offering a lower price. The resulting competition of the RFID vendors will then cause RFID hardware prices to decrease.

The technical standardization of RFID hard and software is already far advanced. RFID infrastructures for collecting EPC data stored on passive RFID transponders have reached a high level of efficiency and reliability. The corresponding frequencies and protocols have been standardized. EPCglobal has also developed the so-called EPC Information Services or EPCIS (EPCglobal [2007a], Goebel and Tribowski [2008]). They are based on the specification of a data format for storing EPC related data, the EPCIS events. EPCIS events contain concise information about the context that has lead to the capture of RFID data, in particular where and why an EPC has been read. According to the vision of EPCglobal, the RFID data collected by the RFID infrastructures installed at the different supply chain stages first gets semantically annotated by an Event Capturing Application. Tribowski et al. [2009b] describe the details of this process and propose standardized solution to transform RFID data into EPCIS events. Afterwards the semantically enriched EPC data is stored in the form of EPCIS events in dedicated EPCIS repositories that serve as a standardized source of EPC related data. Applications that rely on product tracking or tracing data can use the querying facilities offered by the EPCIS to access the EPCIS event data stored in the EPCIS repositories. If granted the corresponding access rights, the EPCIS event repository of one company can also be accessed by information systems via the Internet. Companies can use event data obtained from the repositories of business partners to improve the coordination of their logistic processes, e.g. by realizing Supply Chain Event Management (SCEM) solutions based on EPCIS events (cf. Goebel and Tribowski [2008], Tribowski et al. [2009a]). Other stockholders may also benefit from using standardized product tracing data, e.g. government agencies responsible for assuring legal compliance or end consumers who want to verify the origin and authenticity of the products they acquire. In fact, applications like the RFID-based pedigree imply the standardized access to decentralized RFID data (cf. Staake et al. [2005]). EPCglobal closely coordinates the further development of EPC related standards with potential users from different industries in order to consider their respective business and technical requirements. Many RFID solution vendors have also begun to play an active role in the standardization effort. For instance, major software vendors who offer RFID middle ware solutions such as IBM, SAP, and Oracle, already adhere to the specified EPCglobal standards (cf. e.g. Anonymous [2008]).

Although the benefit of using RFID to monitor the movement of single products in the supply chain is expected to be high in practice (cf. e.g. Goebel et al. [2009b], Thiesse and Condea [2009]), it is still far from being realized. Apart from early trials, for instance the one conducted by the apparel manufacturer Gerry Weber and the retail store chain Kaufhof in 2003 (cf. Loebbecke [2005]), I am not aware of any cross-company application of item level RFID.
One possible explanation for this observation may be a lack of economic incentives. In fact the prevailing consensus in practice is that retailers realize most of the value from item level RFID whereas their suppliers, i.e. the manufacturers and distributors of consumer products, do not gain substantial benefits. The manufacturers and retailers forming part of a consumer good supply chain typically see very different benefits from item level RFID (see, e.g., Kambil and Brooks [2002]). Manufacturers are generally most interested in tracking cases or pallets of the products they deliver to the retailer's distribution centers or outlets, whereas retailers are expected to gain substantial benefit from individual-product tracking on their shelves (Kambil and Brooks [2002], Alexander et al. [2002]). Since item level tags are usually placed within the single product's carton or even sewn into products in the case of apparel, it makes economic sense to tag at the manufacturers' location. Otherwise all recipients of the product who want to use item level RFID would have to operate tag placing and encoding equipment at all of their distribution centers or retail stores. The initial conflict of item level RFID adoption thus becomes clear: Whereas the supplier usually incurs the cost of tagging products, the economic potential is expected to lie

on the retailers' side (cf. Gaukler [2005]). Assuming economically rational behavior, there are only two ways to share tagging costs among supply chain participants. Either the retailer is very powerful and can thus force the manufacturers to tag products without paying for it. Gaukler [2005] uses an economic model to show that the fraction of the tagging cost incurred by the manufacturer depends on the market power of the retailer. However, regarding the fact that even Wal-Mart, despite its overwhelming market power, struggles with making manufacturers tag on the item level, the exploitation of power alone may not be the appropriate way to foster RFID compliance (not to mention RFID usage) of manufacturing companies. Another way to foster RFID adoption and usage in the supply chain is to convince manufacturers that its use in logistical facilities such as distribution centers leads to significant cost savings that justify the investment. According to many recent industry reports, the manufacturers of consumer products are very well interested in using the technology. According to Anonymous [2005] the manufacturers no longer scramble to comply with retail mandates but step back and ask the million dollar question: "Is this just sunk cost, or can we find a way to benefit from it?" Whereas this question seems to be more or less answered with regard to case and pallet level tagging, it remains open with respect to item level tagging. Recent case studies published by Bensel et al. [2008] and Goebel et al. [2009c] suggest that the driving company will in any event incur the initial tagging cost because convincing benefits on the supply side are hard to prove before the actual implementation of item level RFID. However, as Bensel et al. [2008] argue, the tagging cost may be reallocated to participating business partners after item level RFID has been adopted and its benefits materialize along the supply chain.

The following statements summarize our observations regarding the use of item level RFID along the supply chain:

1. The cross-company use of item level RFID enables applications whose overall economic benefit is expected to be high but uncertain.

2. The standardization of RFID related hard and software has reached a high level.

3. Cross-company usage of item level RFID is rare.

4. The lack of cooperative RFID usage is the result of missing economic incentives, in particular at higher stages of the supply chain.

The focus of the work presented in this chapter is the analysis of the economic incentives of manufacturers and retailers to adopt item level RFID. As

we outlined previously, the use of item level RFID not only in retail stores but also at the site where products are made is a crucial precondition for realizing the full potential of RFID. The benefits expected from advanced supply chain applications (e.g. SCEM or efficient product recalls) and innovative consumer oriented services (e.g. product authentication) can only be realized if RFID data is collected, stored, and made accessible in a standardized semantically enriched format (such as the EPC events) along the supply chain.
To date, the academic literature investigating the economic incentives for using item level RFID along the supply chain is sparse. We address this research gap by proposing an economic model that captures the impact of wrong deliveries resulting from picking errors and shrinkage in standard supply chain processes as well as inefficient retail store execution on the incentives of both manufacturers and retailers to use RFID cooperatively. We show that in most cases the cooperative use of RFID, and thus the implementation of RFID infrastructures along the supply chain, is more profitable for both parties. In addition we demonstrate that if the manufacturers are able to completely eliminate wrong deliveries by using RFID, there exist no obvious incentives for information hiding which represents another necessary condition for RFID-based information sharing and thus the realization of more advanced applications such as Vendor Managed Inventory (VMI) or SCEM. The focus on wrong deliveries and shop floor execution has been chosen due to their undisputed economic relevance and straight forward applicability.

In Section 2.2 we review the academic and non-academic literature relevant to the research presented in this chapter. Section 2.3 describes the economic model we use to capture the impact of item-level RFID on the profits of manufacturers and retailers in different usage scenarios. In Section 2.4 we present and analyze the results obtained from an extensive numerical study based on the supply chain model defined in Section 2.3. In Section 2.5, we investigate the strategic implications of possible item-level RFID deployment scenarios. Section 2.7 concludes the research presented in this chapter and outlines the managerial implications of our work.

2.2 Related Research

A number of recently published papers and industry reports investigate the expected impact of RFID on supply chain performance (cf. Thiesse and Condea [2009]). In particular, RFID solution providers and consultants enumerate several benefits expected from the use of RFID in supply chain operations. Meanwhile established industry publications like "The RFID Journal" contain hundreds of case studies and expert claims how RFID can increase business value. Many of these claims have to be handled with care. On the one hand, RFID vendors may exaggerate the potential of RFID in order to sell their solutions. On the other hand, the RFID success stories presented in industry publications can often not be validated by third parties.

Kärkkäinen and Holmström [2002] were among the first to investigate how RFID can create value at different stages of the supply chain. A number of RFID value studies conducted by the Auto-ID Center and associated industry partners also cover several supply chain stages, in particular manufacturing Chappell et al. [2003c], the distribution of retail products Chappell et al. [2003b], and retail stores Chappell et al. [2003a].

The vast majority of empirical works rely on case studies as research methodology. Loebbecke and Huyskens [2007] considers the Metro Group's Future Store Initiative in Germany and the associated RFID pilot project in the retail supply chain. The pilot included the distribution centers of German fashion manufacturer Gerry Weber and department store chain Kaufhof. Apparel products were tagged on the item level and a 100 per cent quantity count was conducted at the goods issue of the upstream distribution center and the goods receipt of the downstream distribution center. To the best of my knowledge, this was the first documented case where the same RFID transponders were used repeatedly on successive supply chain stages and across companies. Other case examples from the retail industry were provided by Delen et al. [2007], Lefebvre et al. [2007], Shim et al. [2007] and Wamba et al. [2006].

In practice, most RFID profitability calculations and therefore adoption decisions have been based on automation benefits, i.e. labor and time savings resulting from process acceleration. On the one hand, these benefits can be computed with relative ease provided the corresponding processes have been analyzed. On the other hand, they can be expected to directly follow from RFID usage which facilitates the task of "selling" these benefits to practitioners. Unfortunately, RFID's value resulting from labor and time savings can hardly be generalized since it heavily depends on company specific practices. For instance, in settings where the properties of the bar code have already been fully exploited to increase the degree of facility automation, RFID often adds little value.
The information value of RFID is generally more emphasized by the academic literature. Benefits in this category are harder to estimate since they

necessitate a model of supply chain control and how this control can be improved by information extracted from RFID data. Despite these difficulties, many research works have been published in this field that showed significant cost saving potential. Some of them are cite in the following.
Chalasani and Sounderpandian [2004] develop a simple analytical model of a retailer who uses RFID to automate his reordering and shelf replenishment process. Fleisch and Tellkamp [2004] present the results of a simulation study on a supply chain with multiple sources of inventory inaccuracies and investigate the impact of RFID on supply chain performance. They were among the first to use a modeling approach for analyzing the RFID value. Lee and Özer [2007] provide a broad overview of recent RFID research in the operations management community. Their focus is on providing methodological background on how the characteristics of RFID can be integrated into classic inventory control models. Gaukler et al. [2007] present analytic models of the benefits of item-level RFID in a prototypical supply chain consisting of a manufacturer and a retailer. In particular, they use an economic modeling approach to determine optimal ways to share the tagging cost among supply chain participants. Heese [2007] considers RFID as a means to avoid inventory inaccuracies and determines the cost thresholds at which RFID adoption becomes profitable. Karaer and Lee [2007] analyze a reverse channel problem that considers the possibility of return information, data which becomes visible to the manufacturer due to the use of RFID.

This chapter makes a contribution to the evolving field of RFID research by analyzing the incentives to use item level RFID on subsequent stages of the supply chain. Instead of focusing the coordination issues resulting from RFID usage solely at retail stores (cf. e.g. Gaukler et al. [2007] and Heese [2007]), we investigate how the ability to efficiently conduct 100 per cent counts in the picking, shipping, and goods receipt processes affects the incentives of a prototypical manufacturer and retailer to adopt item level RFID. Most of the publicly accessible tools for estimating RFID benefits in standard supply chain settings, depending on the viewpoint taken in assessing benefits, consider the use of RFID to prevent "false deliveries" and achieve "compliance". From our own experience in estimating RFID benefits in practice we can tell that these types of benefit often represent the loin's share of total expected benefit.

The relevance of this research arises from the fact that the economic impact of RFID depends to a large degree on its business value for adopting organizations (cf. Schmitt and Michahelles [2008]). As outlined in the introductory section of this chapter, many promising applications only become possible if RFID data is collected on several stages of the supply chain.

2.3 The Model

2.3.1 General Assumptions

The model we use to demonstrate the value and strategic impact of item level RFID in the supply chain has one manufacturer M and one retailer R. We use the term manufacturer only for convenience. It simply denotes the upstream business partner of the retailer which could also be a distributor or wholesaler.
The manufacturer delivers a single product to the retailer. After the retailer has placed an order with the manufacturer, the manufacturer picks the corresponding amount of products from her stock and delivers it to the distribution center or directly to a major outlet of the retailer before the start of the sales period. Making or buying this product costs her c_M Euros. The per unit revenue she earns by selling the product to R is r_M Euros. Thus her profit per unit of product sold is $r_S - c_S$ and the corresponding markup is $m_M = (r_M - c_M)/r_M$. The variable transportation cost that is incurred by the manufacturer is assumed to be included in the production cost.

The retailer sells the product to the end customers. Her profit per unit sold is $r_R - c_R$ Euros where c_R Euros is the purchase cost. The purchase cost is assumed to be equal to the supplier's revenue per unit, i.e. $c_R = r_S$ Euros. We assume that the product is sold for r_R Euros at the retail stores. Thus, the retailer's relative markup is $m_R = (r_R - c_R)/r_R$.
The retailer makes her order decision according to a one period Newsvendor framework (cf. e.g. Nahmias [2005], p. 241). The Newsvendor model is a widely accepted standard for modeling supply chains, especially if simple models for more strategically oriented analyses are required (cf. Cachon [2003]).
If the ordered quantity Q in one period is smaller than the number of units D requested by the end consumers during this period, the retailer incurs lost sale costs equal to $(D - Q)m_R r_R$ Euros. In case the consumers demand less product units than ordered by the retailer, the remaining products can be salvaged at a value of s Euros per item (e.g. by selling it at a discount at the end of the sales period). If the product cannot be used after the sales period, s is equal to zero. The unit salvage value s lies somewhere in between the unit purchasing price of the retailer, i.e. $(1 - m_R)m_R$, and zero. Equation 2.1 provides the formula used to obtain the unit salvage value.

$$s = h(1 - m_R)r_R \tag{2.1}$$

We assume that the "true" consumer demand d during one sales period is a random variable that follows a normal distribution $N_1(\mu_d, \sigma_d)$. If the sum of the period demand for a product at all retail stores is sufficiently high, the Normal Distribution is an acceptable model of consumer demand because the probability of negative values becomes negligible. Let F be the normal Cumulative Density Function (CDF) of $N_1(\mu_d, \sigma_d)$, and let F_1^{-1} be its inverse normal CDF. Define $f_1(x)$ to denote the standard normal Probability Distribution Function (PDF) corresponding to F_1^{-1}. The optimal order quantity according to the Newsvendor model can be computed using the following formula (cf. Nahmias [2005], p. 244):

$$Q = F^{-1}(\frac{c_u}{c_o + c_u}) \tag{2.2}$$

In Equation 2.2 c_u represents the "underage cost" and c_o the "overage cost" per unit. The retailer incurs underage cost if the stocked product quantity does not suffice to satisfy consumer demand. If consumer demand is higher than the number of available stock, she incurs overage cost. In our model the basic underage cost per item is $c_u = r_R - c_R$ and the unit overage cost is $c_o = c_R - s$.

2.3.2 RFID Tagging

We assume that if the retailer decides that she wants her products to be tagged, she has to pay for the entire tagging cost. Only if the manufacturer uses RFID and the retailer does not, the tagging cost is incurred by the manufacturer. According to the results of Gaukler [2005] this is a reasonable assumption if the retailer is not powerful enough to make the manufacturer give up the corresponding profit margin.
The per unit RFID tagging cost is denoted by t. This cost encompasses the price of the RFID transponder itself as well as the cost of attaching the tag to the product and virtually associating the unique identifier with the product type.[1] If the retailer orders tagged products, the tagging cost t is included in the unit purchase price. Therefore the optimal order quantity also depends on t (cf. Gaukler [2005]).

[1] Goebel et al. [2009c] provide some background information about the planned item level tagging processes at Gerry Weber.

2.3.3 RFID's Impact on Store Efficiency

Similar to Gaukler [2005] and others we use the "shelf stock/back room stock" paradigm to model the in store shelf management process. The back room stock is replenished each time a shipment from the manufacturer or the retailer's own distribution center arrives at the retail store. Thereafter products are replenished from the back room to the shelves whenever necessary. Back rooms exist in most retail settings since the space on the actual sales floor is usually limited. The frequency of replenishments depends on the daily demand and other factors such as the availability of personnel responsible for restocking. Similar to Gaukler [2005] and others we assume that the penalty for empty shelves is lost sales.

Item level RFID is expected to allow for "smarter" shelf restocking and thus to help preventing lost sales. We assume that its usage on the sales floor increases the shelf replenishment process to 100 per cent. This also implies the usage of an information system that indicates the need for action and helps store personnel to devise replenishment priorities. The cost of purchasing and implementing such a system is deliberately not part of our model.[2] The only assumption we make is that a further improvement of current shelf management processes is not possible without the additional data quality that can be provided using RFID in the stores. Thus, if the retailer does not use RFID for item level tracking, she incurs a lost sale every time a customer willing to buy or an inquired sales person does not find it on the shelves (although the product may be available in the back room). In particular, we assume that without RFID the effective demand $\bar{d}$ that can be satisfied is only $100(1-\alpha)\%$ of the true demand d. It can easily be seen that if the effective demand $\bar{d}$ for the considered product decreases, the corresponding demand distribution changes from the distribution of the true demand N_1 to $N_0((1-\alpha)\mu_d, \sqrt{(1-\alpha)\sigma_d})$. Let F_0^{-1} denote the corresponding inverse function and $f_0(x)$ denote its PDF (cf. Gaukler [2005], p. 18). Thus, if the retailer does not order RFID tagging and therefore cannot exploit its advantages on the sales floor, she maximizes her profit by ordering the following quantity.

$$Q_0 = F_0^{-1}\left(\frac{r_R - c_R}{r_R - s}\right) \tag{2.3}$$

$$= F_0^{-1}\left(\frac{m_R}{1 - h(1 - m_R)}\right) \tag{2.4}$$

[2] As recent publications on this topic suggest, such systems would not necessarily imply the deployment of RFID readers across the entire sales floor. Rather the installation of readers at certain neuralgic spots in the retail store, e.g. the door of the back room, usually suffices to provide the required data basis (cf. Thiesse and Fleisch [2007]).

If the retailer uses RFID in the stores, she orders the following profit maximizing quantity (cf. Gaukler [2005], p. 19):

$$Q_1 = F_1^{-1}(\frac{r_R - c_R - t}{r_R - s}) \tag{2.5}$$

$$= F_1^{-1}(\frac{m_R}{1 - h(1 - m_R)} - \frac{t}{r_R(1 - h(1 - m_R))}) \tag{2.6}$$

2.3.4 Delivery Errors

We assume that delivery errors have two main underlying causes, namely picking errors and shrinkage. Picking errors occur at the manufacturer's warehouse or distribution center when shipments destined for the retailer are picked and assembled to shipments. If the product variety of products contained in one shipment is relatively large, the complexity and thus the probability of picking errors increases. A typical example for high product variety delivered by the same manufacturer is the apparel sector. Different colors, sizes, and styles easily lead to hundreds of SKUs contained in one shipment. Shrinkage can occur at many steps during the delivery process. Products can be misplaced, stolen or spoilt. According to industry reports, employee theft represents one of the most important sources of shrinkage in the supply channel. High value items are, of course, more likely to be stolen than low value items. We model the effect of delivery errors using two random variables: y for the picking error and z for the shrinkage.
The random variable y is assumed to be distributed according to the normal distribution $N(\mu_y, \sigma_y)$ with zero mean. Thus, according to our model assumptions, picking errors sometimes result in more and sometimes less items than ordered leaving the manufacturer's warehouse. Let $g(y)$ denote the probability distribution function of y in the following. The standard deviation σ_y of this distribution is assumed to multiplicatively depend on the order size in the following way.

$$\sigma_y = \theta_y Q_{\{0,1\}} \tag{2.7}$$

This definition implies the intuitive assumption that the absolute picking error increases with the absolute size of orders. The parameter θ_y scales the variance of over and under deliveries and will be used in the subsequent analyses.

The random variable z is used for modeling the total amount of shrinkage occurring between the production step and the hand over of shipments at the retailer's location. We assume that this shrinkage is distributed according to

the Poisson distribution $P(\lambda_z)$. The reason for choosing the Poisson distribution is that undiscovered shrinkage is usually small relative to the ordered quantity and always positive (in contrast to the picking error). According to Nahmias [2005], the Poisson distribution is a useful model for demand even if its mean is very low. Let $h(z)$ denote the probability distribution function of z in the following. The parameter λ_z of P represents both the mean and the variance of the distribution (cf. Law [2007]).
The mean and variance of the shrinkage occurring in the supply channel are assumed to multiplicatively depend on the order size in the following way.

$$\lambda_z = \theta_z Q_{\{0,1\}} \tag{2.8}$$

Thus, similar to the picking error, we assume that the amount of items that get lost on their way from the manufacturer's warehouse to the retailer's distribution center or outlets depends on the total amount of items being shipped.

The actual quantity that reaches the retailer's distribution center is the quantity ordered plus the picking error minus the shrinkage.

$$\bar{Q}_{\{0,1\}} = Q_{\{0,1\}} + y - z \tag{2.9}$$

2.3.5 RFID Usage in the Supply Chain

The manufacturer tags the products during or right after production. We assume that this approach makes economic sense, whether the manufacturer only "slaps and ships" or uses the transponders in her own processes. Thus, the RFID system can support the following delivery processes of the manufacturer:

1. Put away process (movement of items from production facility to the manufacturer's stock)

2. Picking process (assembly of retailer orders and forwarding to the packing station)

3. Packing process (packing of single items into cartons, onto pallets, etc. and preparation of shipments)

4. Goods issue process (movement of shipments to loading bay)

5. Loading process (movement of shipments onto trucks)

6. Transportation process (transportation of retailer order to the retailer's distribution center or stores)

In each of the mentioned processes, RFID data can be used to validate whether the right quantity of products is allocated to the right shipments. For instance, during the picking process the RFID-based system can continuously compare picked products with the items listed on the current picking list. The use of RFID readers installed on the loading platform of trucks enables quantity checks while the products are in transit to the retailer's location. Thus, both picking errors and shrinkage can be detected immediately and without human intervention using RFID. It is important to note that RFID only allows for detecting process errors, not their actual correction. We assume that only picking errors can be corrected whereas shrinkage can only be prevented in the long term by improving the corresponding processes. A promising moment to detect and correct picking errors is during the picking process or between the picking and the packing process. After products have been bundled up to shipment lots and moved to the loading bay manual intervention is more costly since the entire bundling process may have to be repeated after adjusting the quantities.
RFID readers installed at the loading bay and on board of trucks can be used to validate the completeness of customer orders after they have been loaded onto the waiting trucks and while they are in transit from the manufacturer's to the retailer's location. According to the logistics managers interviewed by Huber and Michael [2007], shrinkage both at loading bays and during transportation is a huge problem. Shrinkage happens for many different reasons, e.g. spoilage, damage, and theft. Product loss in small quantities at loading bays or consolidation sites is often not discovered. Since containers are often not locked or sealed, products may also disappear on their way from one loading bay to the next. While RFID can help to determine the time and place where single items are lost, the prevention of shrinkage is more costly. We assume that using the information won from RFID data allows for identifying the most important sources of shrinkage and finding effective solutions to reduce shrinkage in the long term. Thus, if the manufacturer has the economic incentive to prevent shrinkage and the technical means to find out where and when it occurs, she will take the necessary measures to do so. The ability to efficiently prove the time and place of product loss can already enable the manufacturer to reduce the financial loss resulting from shrinkage. In particular we assume that the manufacturer can use RFID monitoring data to obtain financial compensation from the employees who are responsible for certain process, the third party logistics contractor responsible for the delivery, or the insurance company. For instance, if a 100

per cent product count of a particular truck load results in no quantity error when leaving the manufacturer's facility and reveals a quantity error upon its arrival at the retailer's facility, it is evident that the corresponding number of products got lost during transit. If a third party logistics provider was in charge of the transportation, the manufacturer can hold this provider responsible for the product loss and charge her accordingly.

The retailer can install RFID readers at the goods receipt of her distribution center or outlet. This enables her to conduct a 100 per cent count of incoming shipments. Without RFID this is usually not possible, especially at large distribution centers where trucks arrive in minute cycles (cf. Huber and Michael [2007]). We assume that the actual correction of delivery errors is no longer possible at this point. Products that have not been picked may have already been used to fill orders of another customer. Lost products cannot be recovered because they have either been stolen or are in a non-usable state. Although the retailer may be able to detect product shortage later in the distribution process (e.g. when products get forwarded to the stores) she may not be able to convince the manufacturer or a legal authority that the product was not received in the first place, i.e. that it has not been lost in her own processes. Furthermore, international trade law requires that received shipments are inspected immediately and states that otherwise the buyer is not entitled for compensation if the sales contract has not been fulfilled. If the items being shipped to the retailer are tagged and the retailer has installed readers at her loading bays, she is able to immediately prove under deliveries to the manufacturer. This entitles her to obtain an adequate financial compensation in case too few items of a particular product type have been received.

2.3.6 Profit Functions

There are four generic types of mathematical functions that describe the respective profit of the manufacturer and the retailer. These generic types are provided here and invoked later.

As noted earlier, all profit functions we use in this chapter are based on the classical Newsvendor model (cf. e.g. Nahmias [2005], p. 242). Due to the influence of delivery errors, however, the classical profit functions slightly change depending on who uses item level RFID to monitor the supply chain and takes corrective action based on the access to more accurate and timely information about the flow of goods. The generic profit functions take the order quantity Q and the incurred unit tag price t as arguments.

In the first generic case we consider neither the manufacturer uses RFID in the picking and/or shipping process, nor the retailer at the goods receipt. I this case, undisclosed picking errors and shrinkage do not result in revenue loss for the manufacturer because the retailer is not able to efficiently prove it upon the receipt of shipments. Shrinkage affects the manufacturer's production cost negatively since she is not able to efficiently prove that the product loss occurred during the shipping process. Otherwise the manufacturer would be able to prove the shrinkage to responsible employees, the third party logistics provider, or the insurance company and obtain the production cost back. If fewer products are picked than ordered (negative picking error), the corresponding number of items remains in stock and can be used to fill orders placed by other customers. Due to the assumption that picking more or fewer items than ordered is equally likely (cf. Section 2.3.4), the production cost that is lost by the manufacturer if too many items are picked is balanced out by the value of left over items if too few items are picked.

The following function describes the manufacturer's profit.

$$\Pi_M^0(Q,t) = (1-m_R)r_R Q \tag{2.10}$$

$$- ((1-m_M)(1-m_R)r_R + t)\int_{z=0}^{+\infty}\int_{y=-\infty}^{+\infty}(Q+y+z)g(y)h(z)dydz \tag{2.11}$$

Term 2.10 represents the manufacturer's revenue which is certain in this case, and term 2.11 the expected value of her production cost.

Due to picking errors and shrinkage in the supply channel, the retailer sometimes has more and sometimes less stock for satisfying the effective customer demand. However, since she is not able to prove under deliveries upon the receipt of goods and charge the manufacturer accordingly, she has to pay the purchase price that corresponds to the ordered quantity.

The following function thus describes the retailer's profit in this case.

$$\Pi_R^0(Q,t) = r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{+\infty} \int_{x=-\infty}^{Q+y-z} x f(x) g(y) h(z) dx dy dz \tag{2.12}$$

$$+ r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{+\infty} \int_{x=Q+y-z}^{+\infty} (Q+y-z) f(x) g(y) h(z) dx dy dz \tag{2.13}$$

$$+ h(1-m_R) r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{+\infty} \int_{x=-\infty}^{Q+y-z} (Q+y-z-x) f(x) g(y) h(z) dx dy dz \tag{2.14}$$

$$- ((1-m_R) r_R Q + t) \tag{2.15}$$

The first two terms of the sum (2.12 and 2.13) represent the expected revenue, the third term (2.14) is the expected salvage return, and the last term (2.15) represents the deterministic purchase cost.

If the manufacturer uses RFID in her picking and shipping processes, she is able to detect previously undetectable picking errors and shrinkage in the supply channel. On the one hand, since she knows that the retailer cannot prove false deliveries upon receipt, she will continue to let occasional under deliveries pass without intervention. On the other hand, she has an incentive to detect and correct occasional occurrences of over deliveries. As noted previously, left over items can be used to fill other orders and thus save the corresponding production cost. Since she is also able to pinpoint the location in the supply channel where product shrinkage occurs, she is able to prove it to either the responsible employees, the third party logistics provider, or the insurance company. We assume that this information enables her to get at least the corresponding production cost back.

The generic manufacturer profit can be computed using the following equation.

$$\Pi_M^1(Q,t) = (1-m_R) r_R Q \tag{2.16}$$

$$- ((1-m_S)(1-m_R) r_R + t) \int_{y=-\infty}^{0} (Q+y) g(y) dy \tag{2.17}$$

$$- ((1-m_S)(1-m_R) r_R + t) \int_{y=0}^{+\infty} Q g(y) dy \tag{2.18}$$

Term 2.16 represents the manufacturer's revenue, terms 2.17 and 2.18 her production cost.

The manufacturer's practice of preventing over delivery due to picking errors and ignoring under delivery increases the average negative departure of the delivered from the ordered quantity. Since we assume that the retailer is not able to detect, prove and charge under deliveries efficiently without RFID, she still has to pay for the entire ordered quantity. However, in contrast to the previously described case, the retailer does not receive any more over deliveries. Since having more items on hand is always more beneficial for the retailer, she is strictly worse off in this case.

The retailer's profit can be calculated using the following formula.

$$\Pi_R^1(Q,t) = r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{0} \int_{x=-\infty}^{Q+y-z} x f(x)g(y)h(z)dxdydz \tag{2.19}$$

$$+ r_R \int_{z=0}^{+\infty} \int_{y=0}^{+\infty} \int_{x=-\infty}^{Q-z} x f(x)g(y)h(z)dxdydz \tag{2.20}$$

$$+ r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{0} \int_{x=Q+y-z}^{+\infty} (Q+y-z) f(x)g(y)h(z)dxdydz \tag{2.21}$$

$$+ r_R \int_{z=0}^{+\infty} \int_{y=0}^{+\infty} \int_{x=Q-z}^{+\infty} Q f(x)g(y)h(z)dxdydz \tag{2.22}$$

$$+ h(1-m_R)r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{0} \int_{x=-\infty}^{Q+y-z} (Q+y-z-x) f(x)g(y)h(z)dxdydz \tag{2.23}$$

$$+ h(1-m_R)r_R \int_{z=0}^{+\infty} \int_{y=0}^{+\infty} \int_{x=-\infty}^{Q-z} (Q-z-x) f(x)g(y)h(z)dxdydz \tag{2.24}$$

$$- ((1-m_R)r_R Q + t) \tag{2.25}$$

The first four terms (2.19 - 2.22) represent the retailer's expected revenue, terms 2.23 and 2.24 is the expected salvage return, and the last term (2.25) represents the purchase cost.

If the retailer is able to detect under deliveries using RFID readers at her goods receipt, she can prove them to the manufacturer right upon the receipt of shipments. We assume that this suffices to get the corresponding purchase price back. Thus, the purchase cost of the retailer and therefore the manufacturer's revenue decrease due to this practice.
The profit of the manufacturer can be computed according to the following

expression.

$$\Pi_M^2(Q,t) = (1-m_R)r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{0} (Q+y-z)g(y)h(z)dydz \tag{2.26}$$

$$+ (1-m_R)r_R \int_{z=0}^{+\infty} \int_{y=0}^{+\infty} (Q-z)g(y)h(z)dydz \tag{2.27}$$

$$- ((1-m_M)(1-m_R)r_R + t) \int_{y=-\infty}^{+\infty} (Q+y)g(y)h(z)dydz \tag{2.28}$$

The terms 2.26 and 2.27 represent the manufacturer's revenue; term 2.28 her production cost.

As mentioned above, the retailer benefits from the ability to detect under deliveries using RFID by saving the purchase price for the under delivered items. However, there are further trade-offs to be considered in order to compute her profit. In case she receives fewer items than ordered, the retailer still cannot satisfy demand in the optimal way because less than the optimal order quantity Q has delivered. If there exists structural under delivery due to shrinkage in the supply channel, she still earns less revenue and incurs higher lost sale cost compared to receiving the optimal order quantity. On the other hand, since the manufacturer does not use RFID to monitor the picking process, she will sometimes also over deliver. In this case we assume that the retailer uses the over delivered products to satisfy demand or salvages them if there is no demand left to satisfy. Undiscovered over deliveries, similar to the ability to make the manufacturer pay for under deliveries, thus have a positive effect on the retailer's profit.

The retailer's profit can be calculated using the following formula.

$$\Pi_R^2(Q,t) = r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{+\infty} \int_{x=-\infty}^{Q+y-z} xf(x)g(y)h(z)dxdydz \tag{2.29}$$

$$+ r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{+\infty} \int_{x=Q+y-z}^{+\infty} (Q+y-z)f(x)g(y)h(z)dxdydz \tag{2.30}$$

$$+ h(1-m_R)r_R \int_{z=0}^{+\infty} \int_{y=-\infty}^{+\infty} \int_{x=-\infty}^{Q+y-z} (Q+y-z-x)f(x)g(y)h(z)dxdydz \tag{2.31}$$

$$- ((1-m_R)r_R + t) \int_{z=0}^{+\infty} \int_{y=-\infty}^{0} (Q+y-z)g(y)h(z)dydz \tag{2.32}$$

$$- ((1-m_R)r_R + t) \int_{z=0}^{+\infty} \int_{y=0}^{+\infty} Qg(y)h(z)dydz \tag{2.33}$$

The first two terms (2.29 and 2.30) represent the expected revenue, the third term (2.31) is the expected salvage return, and the last two terms (2.32 and

2.33) represent the purchase cost.

If both, the manufacturer and the retailer use RFID to monitor their respective part of the supply chain, the former will correct both over and under deliveries. The manufacturer prevents over delivery since she can save production cost. She prevents under delivery because she would otherwise incur a per unit penalty of $r_M - c_M$ or $m_M(1 - m_R)r_R$ due to the retailer's charge back policy. The retailer will thus always receive the ordered quantity and can satisfy demand in the optimal manner. The corresponding profit equations are equal to the standard Newsvendor equations.

The manufacturer's profit can be computed as follows.

$$\Pi_M^4(Q,t) = (1 - m_R)r_R Q \tag{2.34}$$
$$- ((1 - m_M)(1 - m_R)r_R Q + t) \tag{2.35}$$

Term 2.34 represents the manufacturer's revenue; term 2.35 her production cost.
The retailer's profit is as follows.

$$\Pi_R^4(Q,t) = r_R \int_{x=-\infty}^{Q} xf(x)dx \tag{2.36}$$
$$+ r_R \int_{x=Q}^{+\infty} Qf(x)dx \tag{2.37}$$
$$+ h(1 - m_R)r_R \int_{x=-\infty}^{Q} (Q - x)f(x)dx \tag{2.38}$$
$$- ((1 - m_R)r_R + t)Q \tag{2.39}$$

The first two terms (2.36 and 2.37) represent the revenue, term 2.38 the salvage value, and the last term (2.39) is the purchase cost.

2.3.7 Scenarios

Depending on who adopts RFID and the purpose it is used for by the respective company, the outcome in terms of cost incurred and benefits obtained differs substantially. Table 2.1 provides an overview of the considered RFID usage scenarios. Assuming that tagging products at the retailer's location does not make economical sense, we excluded these cases from the analysis. Moreover, we excluded scenarios where the manufacturer tags her products and offers the them at no additional cost to the retailer since this would not be individually rational. Provided these generic profit functions and the general model setup described in Section 2.3.1, we will discuss the profit

			Retailer		
			No use of RFID (status quo)	Use of RFID in stores	Use of RFID at goods receipt and in stores
Manufacturer	No cooperation	No attachment of tags (benchmark scenario)	Scenario A: The manufacturer does not comply with the tagging request of the manufacturer or stops tagging on the item level	-	-
		Attachment and use of incompatible tags in the picking and delivery process	Scenario B: The manufacturer uses own tags to prevent over deliveries due to picking errors and obtain the value of products that are lost due to shrinkage	-	-
	Cooperation	Attachment of compatible tags; no use of the tags	-	Scenario C: The manufacturer only attaches RFID tags but does not use them; the retailer uses RFID to increase store efficiency	Scenario D: The manufacturer only attaches RFID tags but does not use them; the retailer uses RFID to increase store efficiency and to implement an RFID-based compensation policy
		Attachment and use of compatible tags in the picking and delivery process	-	Scenario E: The manufacturer uses RFID to prevent over deliveries due to picking errors and obtain the value of products that are lost due to shrinkage ; the retailer uses RFID to increase store efficiency	Scenario F: The manufacturer uses RFID to prevent false deliveries altogether by preventing picking errors and shrinkage; the retailer uses RFID to increase store efficiency and to implement an RFID-based compensation policy

Table 2.1: Overview of RFID usage scenarios

obtained by the manufacturer and the retailer in each of the six considered RFID usage scenarios.

Scenario A

In scenario A neither the manufacturer nor the retailer have adopted RFID because, for instance, the manufacturer choses not to comply with the retailer's tagging request. This may be the case for various reasons, among others strategical ones. Since the retailer depends on the manufacturer regarding product tagging, she is not able to use RFID in this scenario. In particular, she cannot increase shop floor efficiency which makes the effective demand fall short of the true demand. Since she does not receive tagged products, however, she also does not bear any tagging costs in this case. Therefore the retailer will place an order of size Q_0 (cf. Equation 2.3). The delivery error stays on its "natural" level and has the influences described in the preceding section.
The functions described in section 2.3.6 are invoked in the following way in scenario A.

$$\Pi_M^A = \Pi_M^0(Q_0, 0) \tag{2.40}$$

$$\Pi_R^A = \Pi_R^0(Q_0, 0) \tag{2.41}$$

Scenario B

There may be situations in which in makes sense for the manufacturer to use RFID alone and actively restrict the use by the retailer. In such a case she would use tags that the retailer cannot read. Preventing subsequent partners in the supply chain from using RFID transponders is easy. In fact, it suffices if the manufacturer uses a secret numbering scheme that the retailer cannot interpret. Another way would be "killing" the transponders when the batches of tagged products pass the goods issue or are unloaded from the truck at the retailer's location. The corresponding profit function invocations are provided below. In the drafted scenario the manufacturer is able to prevent over delivery and obtain money back if products get lost in the supply channel. However, she also has to pay the full tagging cost. The retailer is negatively affected by under delivery and cannot obtain any money back. Moreover her order quantity is lower since she cannot use RFID in the store environment for increasing shelf availability.
In scenario B, the functions described in section 2.3.6 are invoked in the following way.

$$\Pi_M^B = \Pi_M^1(Q_0, t) \tag{2.42}$$

$$\Pi_R^B = \Pi_R^1(Q_0, 0) \tag{2.43}$$

Scenario C

In scenario C the manufacturer "slaps and ships" on the retailer's request. The tagging cost is thus incurred by the retailer. Furthermore, the retailer only uses RFID to increase the efficiency of the store replenishment processes, but not to monitor the manufacturer's delivery compliance. The retailer can now satisfy the true demand which is assumed to be higher due to RFID usage in the stores. Her order quantity thus changes from Q_0 to Q_1.
The following invocations of the generic profit functions characterize the scenario.

$$\Pi_M^C = \Pi_M^0(Q_1, 0) \tag{2.44}$$

$$\Pi_R^C = \Pi_R^0(Q_1, t) \tag{2.45}$$

Scenario D

In scenario D the retailer uses RFID data both to prove under deliveries at the goods receipt and to enable higher store efficiency. This enables her to sell more products in case she can increase store efficiency and to get back money in case the manufacturer under delivers. The manufacturer simply complies with the retailer's wish to tag products without using RFID data herself. The retailer can therefore benefit from the over deliveries that are not prevented by the manufacturer. On the other hand, under deliveries and shrinkage have a negative impact on profits that cannot be fully compensated by the charge back policy.
Scenario D has the following profit function invocations:

$$\Pi_M^F = \Pi_M^2(Q_1, 0) \tag{2.46}$$

$$\Pi_R^F = \Pi_R^2(Q_1, t) \tag{2.47}$$

Scenario E

In scenario E the manufacturer tags products upon the retailer's request. Hence the retailer has to pay for the tags. The manufacturer uses the compatible tags in order to prevent over delivery resulting from picking errors and to get money back in the event of shrinkage. The retailer on the other hand uses RFID only inside her stores and is thus not able to prove under

delivery upon the receipt of shipments.
The following invocations of the generic profit functions characterize the scenario.

$$\Pi_M^E = \Pi_M^1(Q_1, 0) \tag{2.48}$$

$$\Pi_R^E = \Pi_R^1(Q_1, t) \tag{2.49}$$

Scenario F

In scenario F RIFD is used in all considered areas of the supply chain. The manufacturer uses it to prevent picking errors and shrinkage in the supply channel while the retailer uses it to check the manufacturer's compliance with regard to the shipped product quantities and to increase the self availability in her stores. The retailer is assumed to pay the entire tagging cost. On the one hand, deliveries are reliable in this case since the manufacturer delivers the ordered quantity. On the other hand, store efficiency is maximized because the retailer satisfies the true customer demand with the optimal quantity of products.
The profit function invocations in scenario F are as follows.

$$\Pi_M^F = \Pi_M^3(Q_1, 0) \tag{2.50}$$

$$\Pi_R^F = \Pi_R^3(Q_1, t) \tag{2.51}$$

2.4 Numerical Study

2.4.1 Experimental Setup

Solving the profit functions provided in Section 2.3.6 is difficult due to several reasons.
Firstly, the bounds of inner integrals often depend on the integrands of the outer integrals. Secondly, the convolution of two random variables where one of them is distributed according to a Normal and one according to a Poisson distribution is mathematically difficult. Thirdly, all model parameters except the random variables y and z representing the picking and shrinkage errors directly affect the optimal order quantity. The order size has an effect on the distribution of picking errors and shrinkage since they multiplicatively depend on it (cf. Equations 2.7 and 2.8). The mean and variance of the picking and shrinkage errors in turn affect the expected profit of both the supplier and the retailer if errors are not completely prevented like in scenario F. The

complexity of these interdependencies makes a purely mathematical treatment of the impact of picking errors and shrinkage and thus the expected value of RFID difficult. Hence we resort to numerical simulation.

Numerical integration can be a powerful tool for computing integrals if the parameters of the corresponding probability distributions are known. Therefore it can be used to compute the profit functions of Section 2.3.6 for fixed parameter configurations. The number of parameter configurations that can be analyzed using the approach is limited by the available computational resources and the effort of analyzing the results. Therefore the combination of parameter values has to be chosen with care in order to draw useful conclusions based on the results obtained from the numerical computation.
Table 2.2 lists the parameters and corresponding values that we use as input for the model. We have chosen parameter ranges that are suitable to

Parameter	Values	Description
r_R	$\{20, 40^*, 60\}$	Unit sales price
m_R	$\{20\%, 30\%^*, 40\%\}$	Percentage retail markup
m_S	$\{20\%, 30\%^*, 40\%\}$	Percentage wholesale markup
h	$\{0, 0.2^*, 0.4\}$	Factor of salvage value (cf. Equation 2.1)
t	$\{0.05, 0.1^*, 0.15\}$	Unit RFID transponder cost
μ_d	$\{500, 1000^*, 1500\}$	Mean end consumer demand d
σ_d	$\{50, 100^*, 150\}$	Standard deviation of end consumer demand d
θ_y	$\{0\%, 0.1\%, ..., 1\%\}$	Factor of the standard deviation of the yield error y (cf. Equation 2.7)
θ_z	$\{0\%, 0.1\%, ..., 1\%\}$	Factor of the mean and variance of shrinkage in the supply channel z (cf. Equation 2.8)
α	$\{0\%, 0.25\%^*, 5\%\}$	Demand lost due to inefficient store processes

Table 2.2: Model parameters (* indicates default value)

describe the properties of high-impact consumer products (cf. Chapter 1). Those products are often not repeatedly ordered from the manufacturer but rather delivered in high quantities at the beginning of the sales season (e.g. apparel, DVDs, etc.). Since they are replaced by new product versions or styles in the next sales season, no second order for the same product is placed with the manufacturer. Therefore the one period Newsvendor model we use in this chapter reflects real world circumstances fairly well.
We focus on rather high priced products which is reflected by the considered retail price range (20 to 60 Euros). This range covers the average price of DVDs, books, apparel, footwear and certain types of consumer electronics.

The relatively high retail and wholesale markup percentages reflect the assumption that the value of the products under consideration quickly diminishes after the targeted sales period. In fact, the Newsvendor model obtained its name from the fact that it can be used to model supply chains providing "fashion goods" whose value perishes rather quickly (newspapers are an extreme example). Most fashion or "innovative" products have rather high markups (cf. Lee [2002], p.106) because there are few or no substitutes for them during their life cycles.
Since the average unit RFID tag price was about 5 Eurocents at the time this dissertation was written, the range of the tagging cost t should reflect reality relatively well provided that automatic tagging equipment is used.
The chosen range of the mean consumer demand μ_d should be regarded as the retailer's mean estimated demand for one stock keeping unit (SKU) during the entire sales season, i.e. the aggregate demand for this SKU at all outlets operated by the retailer for as long as the product is sold there.
The values chosen for the standard deviation of consumer demand σ_d reflect different levels of demand uncertainty. They are, however, significantly higher than the standard deviation of the Poisson distribution which is often used in the operations management literature (cf. Zipkin [2000], p. 179).
The scaling factor θ_y was chosen in a conservative fashion: According to the chosen distribution, the 95% confidence interval at $Q = 1,000$ and $\theta_y = 1\%$ is $(-19.6, 19.6)$. Thus, the delivery errors resulting from the highest considered intensity of the picking error leads a percentage departure of the delivered quantity from the ordered quantity of no more than 2% in 95 out of 100 cases.
The chosen values range for the factor of the mean and variance of shrinkage in the supply channel (θ_z) reflects the fact that high value products are more likely to be stolen in transit from one supply chain stage to the other. According to the chosen distribution, the 95% confidence interval at $Q = 1,000$ and $\theta_z = 1\%$ is $(0, 15)$. Thus, the delivery errors resulting from the highest considered intensity of shrinkage in the supply channel leads a percentage departure of the delivered quantity from the ordered quantity of no more than 1.5% in 95 out of 100 cases.
The factor α is used to scale the degree of store efficiency. Wong and McFarlane [2003] estimate the efficiency of the retail replenishment process from back room to shelf at 90-93%; surveys by ECR Europe carried out by Roland Berger Strategy Consultants [2003] quote similar numbers. The chosen range of α seems conservative regarding these empirical observations. In a recent publication DeHoratius and Raman [2008] empirically show that shelf availability can among other things by explained by product price, i.e. more valuable products are out of stock less frequently. The existent lack of shelf

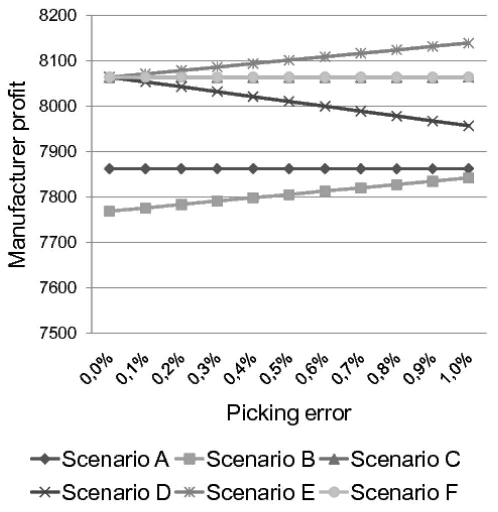
availability in high price settings should thus not be over estimated.

2.4.2 Results

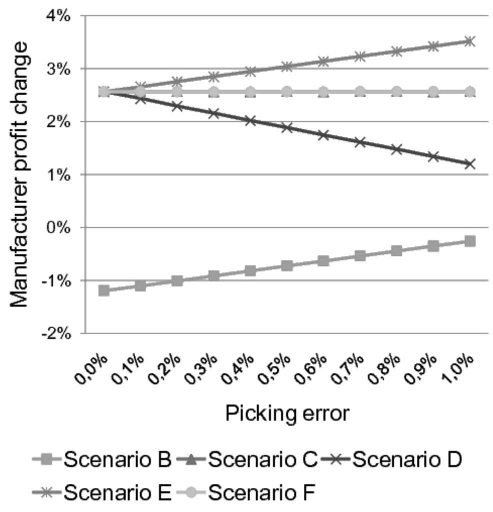
We present the results of the numerical study in two steps. In this section we provide both the absolute profit levels of the supply chain participants in the different scenarios and the percentage change of profit when moving from the status quo where RFID is not used at all (scenario A) to every other considered RFID usage scenario (scenarios B-F). This allows for comparisons of RFID's impact depending on its usage along the supply chain. Throughout the analysis presented in this section, however, we fix the parameters that describe the general supply chain setting at their respective default values (i.e.$r_R = 40$, $m_R = 30\%$, $m_M = 30\%$, $h = 0.2$, $t = 0.1$, $\mu_d = 1000$, and $\sigma_d = 100$) and only change the intensity of the different error sources, i.e. the variance of the picking error (θ_y) and the mean and variance of shrinkage (θ_z).
We first present the results obtained for the manufacturer and later the results for the retailer.

RFID's Impact on the Manufacturer

Figure 2.1 shows the impact of picking errors on the profit of the manufacturer in the different scenarios. Picking errors have no influence on the manufacturer's profit in scenarios A, C, and F. In scenarios A and C the manufacturer's revenue only depends on the ordered quantity since picking errors and shrinkage remain undiscovered. In scenario F picking errors are completely prevented. The manufacturer's profit in the scenarios C and F is higher than in scenario A since the manufacturer benefits from the higher demand of the retailer who uses RFID to increase the efficiency of her stores. The manufacturer's profit in scenarios B and E increases linearly with higher picking errors since the manufacturer is able to save a fraction of the production cost by preventing over delivery. The profit in scenario B is lower than in scenario E because the retailer cannot use RFID on the sales floor in this case. In the considered range of the picking error, the manufacturer's absolute profit is highest in scenario E followed by both scenario C and F, then scenario A, and finally scenario B.
At the highest considered level of the picking error the percentage profit increase achieved by moving from the status quo (no RFID adoption) to cooperative RFID usage ranges between 1.2% in scenario D and 3.5% in scenario E.



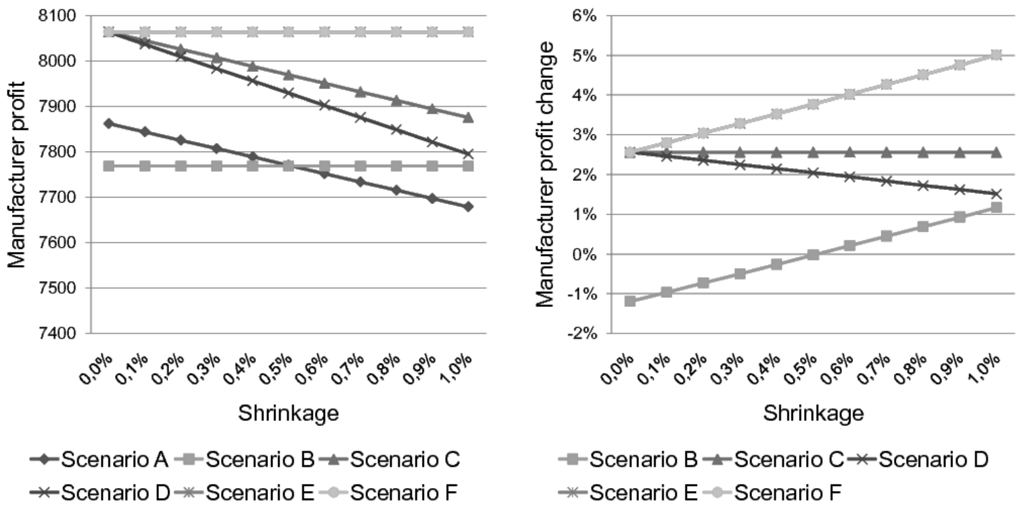
(a)



(b)

Figure 2.1: Absolute (a) and relative profit (b) of the manufacturer in the presence of picking errors

Figure 2.2 shows the impact of shrinkage in the supply channel on the profit of the manufacturer in the different scenarios. Shrinkage has no influence on the manufacturer's profit in scenarios B, E, and F. In scenario B the production value of lost products is retained and the corresponding under deliveries have no impact on the manufacturer's profit since the retailer cannot detect them. The same applies to scenario E. In scenario F we assume that shrinkage is prevented altogether. The profit in scenarios E and F is higher than in scenario B because the retailer orders more (due to RFID-based store processes) and also pays for tagging products. In scenarios A and C shrinkage causes a loss of value corresponding to the production cost. This negative effect is more pronounced in scenario C compared to scenario A since the amount of products flowing through the supply chain is higher. In scenario D, the losses from shrinkage are higher than in scenario C since here the manufacturer not only loses the per unit production cost of every lost item, but also the per unit margin since the retailer is assumed to obtain the wholesale price back. The manufacturer's profits in the scenarios B, C, and D decrease linearly with higher levels of shrinkage.
At the highest considered level of shrinkage, i.e. 1% of the ordered amount, the percentage profit increase achieved by moving from the status quo (no RFID adoption) to cooperative RFID usage ranges between 1.5% in scenario D and 5% in scenarios E and F.



(a) (b)

Figure 2.2: Absolute (a) and relative profit (b) of the manufacturer in the presence of shrinkage

Figure 2.3 shows the combined impact of picking and shrinkage errors on the profit of the manufacturer in the different scenarios. Only the profit in scenario F remains unaffected by the total delivery error since since both picking errors and shrinkage are completely prevented in this case. Due to the manufacturer's ability to prevent over delivery, her profit in the scenarios B and E constantly increases with higher levels of the total delivery error. Her profit in scenarios A, C, and D on the other hand decreases with the combined increase of picking errors and shrinkage. For the case of scenarios A and C this can be attributed to shrinkage. In scenario D it is due both to shrinkage and the picking errors that lead to under delivery.
At the highest considered total yield error, i.e. $\sigma_y = 0.01Q_{0,1}$ and $\lambda_z = 0.01Q_{0,1}$, the percentage profit increase achieved by moving from the status quo (no RFID adoption) to cooperative RFID usage ranges between 1.2% in scenario D and 6% in scenario F.

We record the following results for further usage in the following sections.

Result 1 *(Relationship of manufacturer profits in the case of no cooperation)*

Up to a certain level $(\theta_y, \theta_z)^*$ of the total delivery error, scenario A is more profitable for the manufacturer than scenario B. From $(\theta_y, \theta_z)^*$ onwards, scenario B is more profitable for the manufacturer.

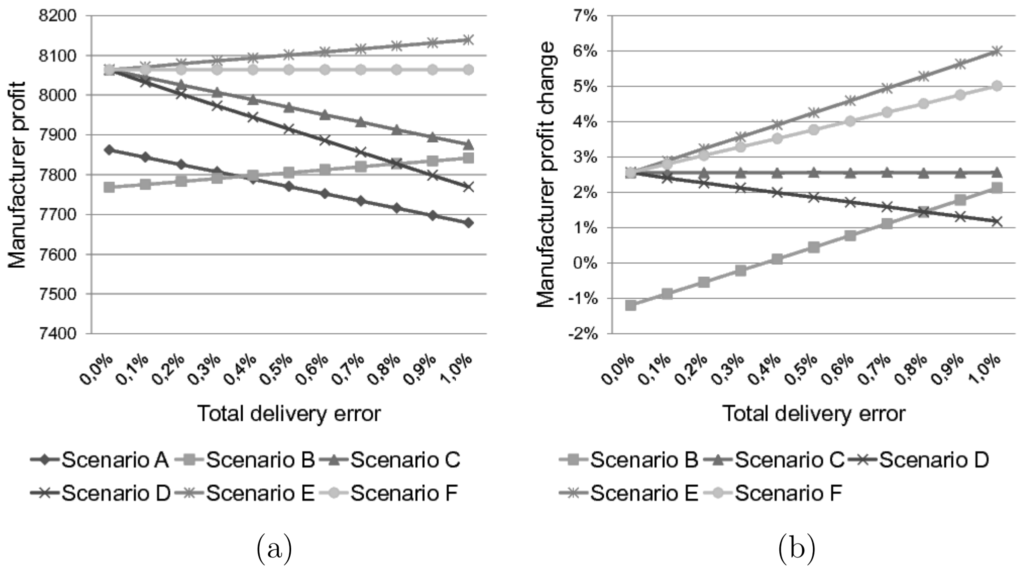


Figure 2.3: Absolute (a) and relative profit (b) of the manufacturer in the presence of picking errors and shrinkage

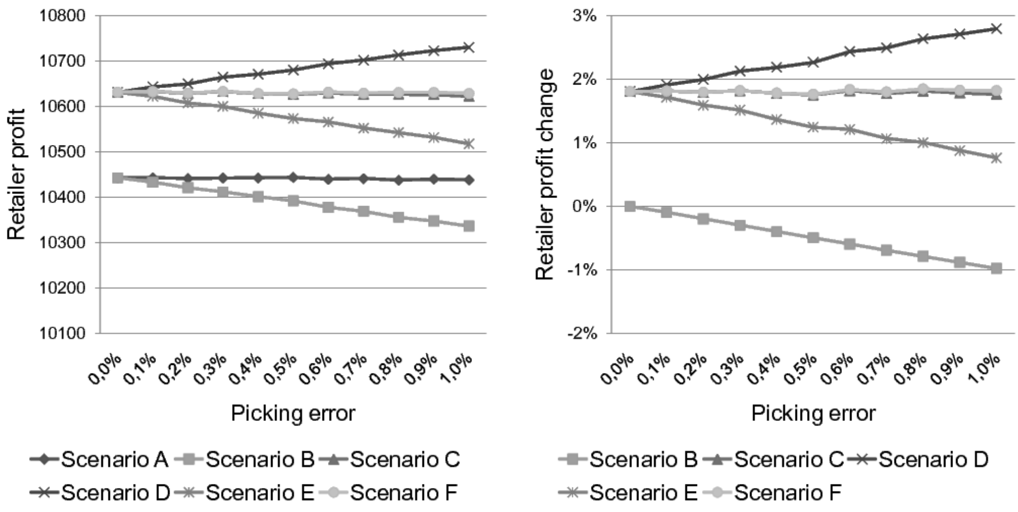
Result 2 *(Relationship of manufacturer profits in the case of cooperation)*

At positive values of θ_y and/or θ_z, the profit obtained by the manufacturer in scenario E is always higher than in scenario C.

At positive values of θ_y and/or θ_z, the profit obtained by the manufacturer in scenario F is always higher than in scenario D.

RFID's Impact on the Retailer

Figure 2.4 shows the impact of picking errors at the manufacturer's location on the absolute and relative profit of the retailer in the considered scenarios. Within the considered range of the picking error, the retailer's profit is not significantly affected in scenarios A and F. In scenarios A occasional under deliveries seem to be balanced out by occasional over deliveries. In scenario F picking errors do not occur since they are prevented using RFID. Whereas the retailer's profit steadily increases with higher levels of the picking error in scenario D, it constantly falls in scenarios B, C and E. This is due to the fact that in scenario D the retailer is compensated in case of under deliveries. In scenarios B and E, on the other hand, she only loses revenue because the picking error in combination with the manufacturer's practice of preventing over delivery leads to a negative departure of the delivered from the ordered quantity. In scenario C the retailer's profit also slightly decreases since the



(a) (b)

Figure 2.4: Absolute (a) and relative profit (b) of the retailer in the presence of picking errors

additional variance of supply introduced by the picking errors is not considered by the order decision.
At a sufficiently high level of the picking error, the retailer's profit is highest in scenario D, followed by the scenarios F, C, E, A, and finally scenario B. At the highest considered level of the picking error at the manufacturer site, the percentage profit increase on the retailer's side that can be attained by moving from the status quo (no RFID adoption) to cooperative RFID usage ranges between 0.8% in scenario E and 2.8% in scenario D.

Figure 2.5 shows the impact of shrinkage occurring in the supply channel on the absolute and relative profit of the retailer in the different scenarios. The only scenario in which the retailer is not affected by shrinkage in the supply channel is scenario F because it is assumed to be prevented in this scenario. Its impact on the retailer's profit in all other scenarios is negative and increasing with higher average shrinkage rates. In scenario D its impact is less negative than in scenarios C and E since the retailer can at least obtain the corresponding purchase price. From the retailer's point of view, scenarios A and B are even worse than scenarios C and E since in these scenarios she suffers both from unobserved under delivery and her inability to increase the store efficiency using RFID.
At the highest considered level of the picking error, the retailer's profit is highest in scenario F, followed by scenario D, C and E (same values), and

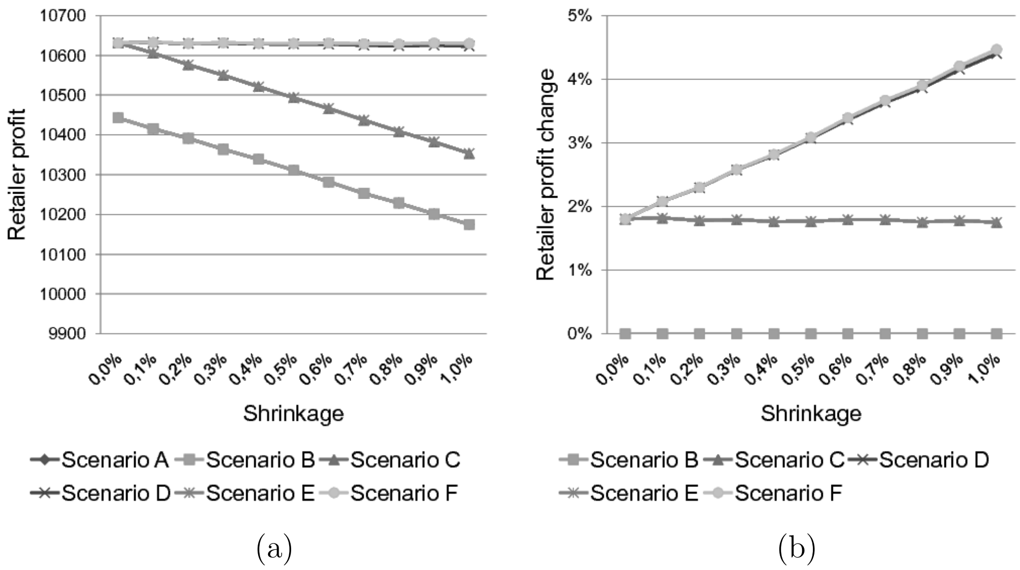


Figure 2.5: Absolute (a) and relative profit (b) of the retailer in the presence of shrinkage

finally scenarios A and B (same values). At the highest considered level of shrinkage in the supply channel, the retailer's profit from cooperative RFID usage ranges between 1.8% in scenarios C and E, and 4.5% in scenario F.

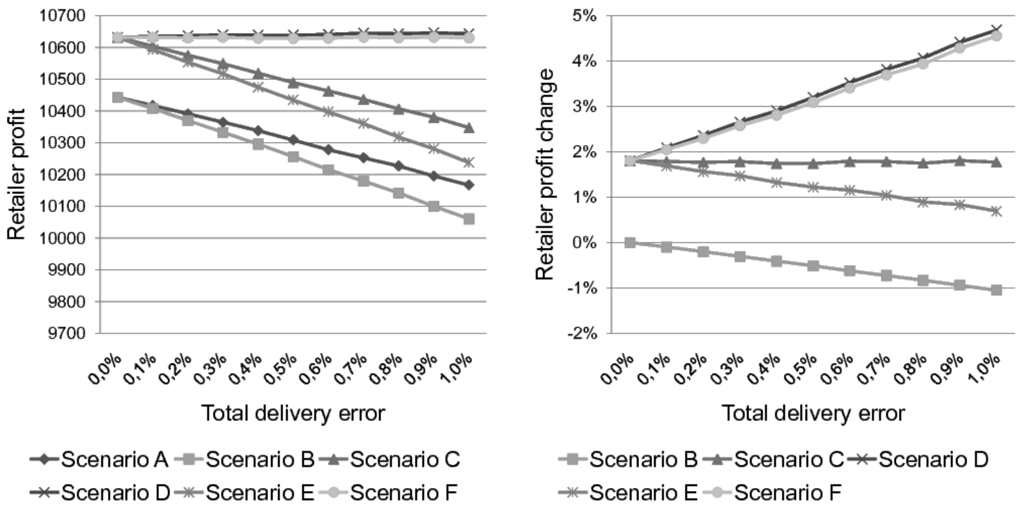
Figure 2.6 shows the combined impact of picking errors and shrinkage in the supply channel on the absolute and relative profit of the retailer in the different scenarios. In all scenarios beside scenario F where delivery errors are prevented by the manufacturer, the retailer's profit linearly decreases while the total delivery error increases. In scenario D the positive effect of sometimes being able to satisfy more demand by using over delivered items (due to picking errors) leads to a slight advantage compared to scenario F. The profit in scenario D is the highest, followed by scenarios F, C, E, A and B.

At the highest considered total delivery error, the percentage profit change resulting from cooperative RFID usage ranges between 0.7% in scenario E and 4.7% in scenario D.

We record the following results for further usage in the following sections.

Result 3 *(Relationship of retailer profits in the case of no cooperation)*

At positive values of θ_y and/or θ_z, the profit obtained by the retailer in scenario A is always higher than in scenario B.



(a) (b)

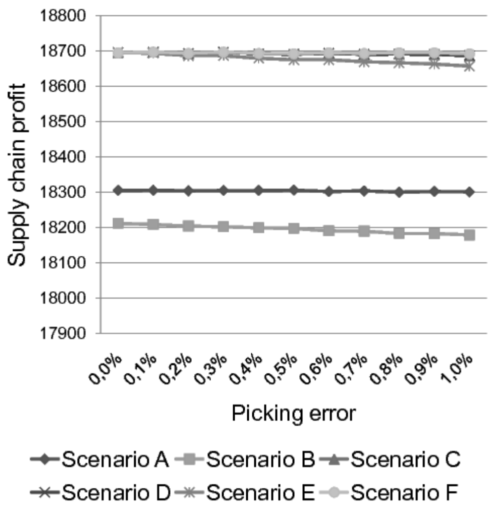
Figure 2.6: Absolute (a) and relative profit (b) of the retailer in the presence of picking errors and shrinkage

Result 4 *(Relationship of retailer profits in the case of cooperation)*
At positive values of θ_y and/or θ_z, the profit obtained by the retailer in scenario F is always higher than in scenario E.

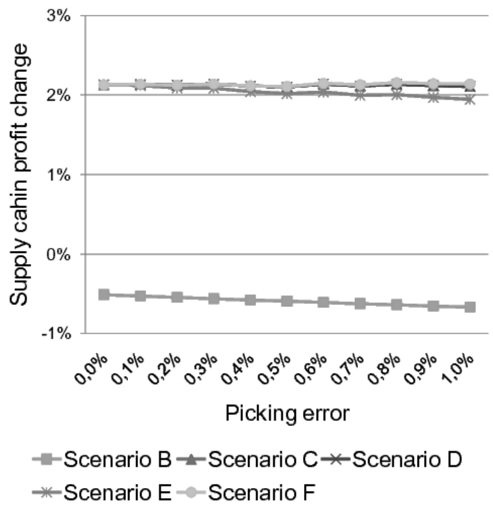
RFID's Impact on the Supply Chain

Figure 2.7 shows the impact of picking mistakes committed in the manufacturer's warehouse on the absolute and relative profit of the entire supply chain in the considered scenarios. The supply chain profit in scenario F remains constant since neither the manufacturer's nor the retailer's profit function is affected by picking errors. The profit of the entire supply chain achieved in the scenarios C, D, and E decreases only slightly with higher levels of the picking error. The profit in scenario A is not influenced by the picking error and significantly lower than the profit realized in the cooperative scenarios. The supply chain profit realized in scenario B is always lower than in all other scenarios and strictly decreasing with increasing levels of the picking error.
At the highest considered degree of the picking error, the percentage profit change resulting from cooperative RFID usage compared to the status quo ranges between 2.0% in the scenario E and 2.1% in scenario F.

Figure 2.8 shows the impact of shrinkage on the absolute and relative supply



(a)

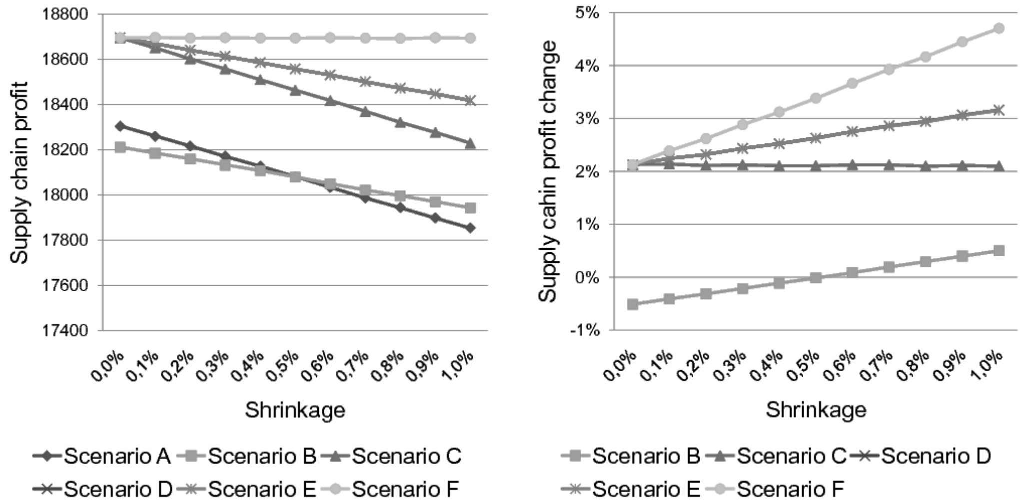


(b)

Figure 2.7: Absolute (a) and relative supply chain profit (b) in the presence of picking errors

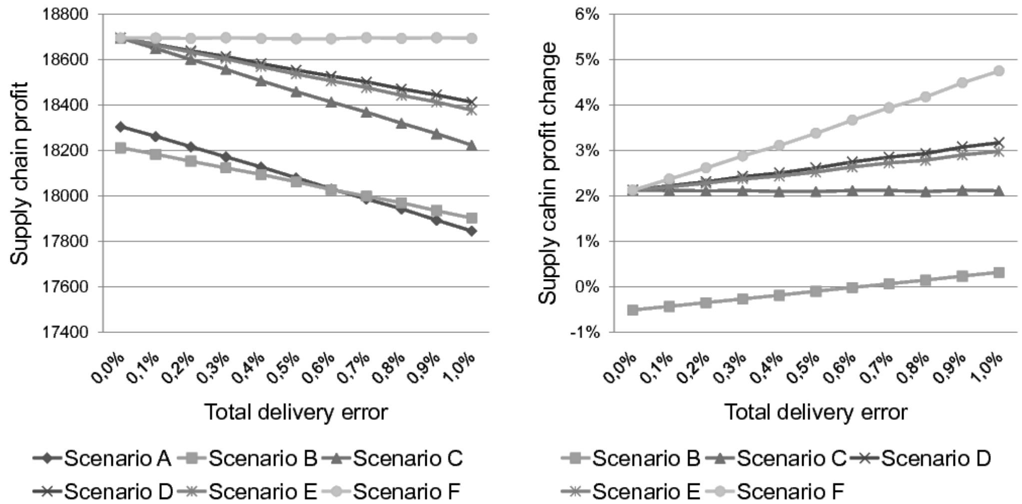
chain profit in the different scenarios. In scenario F shrinkage is prevented and thus has no effect on the supply chain profit. In all other scenarios it has a negative impact. The second best profit is achieved in scenarios D and E (same values). Scenario C is strictly less profitable than all other cooperative scenarios but still more profitable than the non-cooperative scenarios. In scenario A the supply chain realizes more profit than in scenario B up to a certain level of the considered shrinkage range. From this level onwards, scenario B is more profitable than scenario A. This result is due to the tradeoff between the tagging cost and the production cost that can be saved by the manufacturer.
At the highest shrinkage level we consider, the percentage increase of the supply chain's profit from the cooperative use of RFID ranges between 2.1% in scenario C and 4.7% in scenario F.

Figure 2.9 shows the combined impact of picking errors and shrinkage on the absolute and relative profit of the supply chain in the different scenarios. If both picking errors and shrinkage are present, the ranking of the scenarios at $\theta_y = \theta_z = 1\%$ starting with the highest profit scenario is as follows: F, D, E, C, B, A. The absolute profit of the supply chain in the scenarios D and E differs only marginally in the considered error range, i.e. in terms of total profit it does not seem to matter if the retailer uses RFID data to charge the manufacturer for under deliveries (scenario D) or the manufacturer uses



(a) (b)

Figure 2.8: Absolute (a) and relative profit (b) of the retailer in the presence of shrinkage



(a) (b)

Figure 2.9: Absolute (a) and relative supply chain profit (b) in the presence of picking errors and shrinkage

RFID data to save production cost (scenario E). At the highest considered total yield error, the percentage increase of the supply chain profit resulting from cooperative RFID usage ranges between 2.1% in scenario C and 4.8% in scenario F.

2.4.3 Sensitivity Analysis

To make sure that the results presented in section 2.4.2 are sufficiently robust within the range of considered parameter values and to show the effect of the different parameters on the value of RFID, we conduct a sensitivity analysis in this section. In the course of the analysis we recompute the relative profit changes obtained when moving from the status quo, i.e. no RFID adoption, to each of the considered RFID usage scenarios for the lowest and highest value of every considered model parameter respectively. Throughout the sensitivity analysis the level of picking errors and shrinkage are set to their highest respective value in order to render the differences in terms of relative profit change more visible.

Figure 2.10 reveals the sensitivity of the relative profit changes resulting from RFID usage with respect to the unit sales price r_R. The absolute level of the retail price affects absolute profits in manifold ways since it shows up in every single term of the manufacturer's and the retailer's profit functions (cf. Section 2.3.6). The changes of the manufacturer's profit in response to

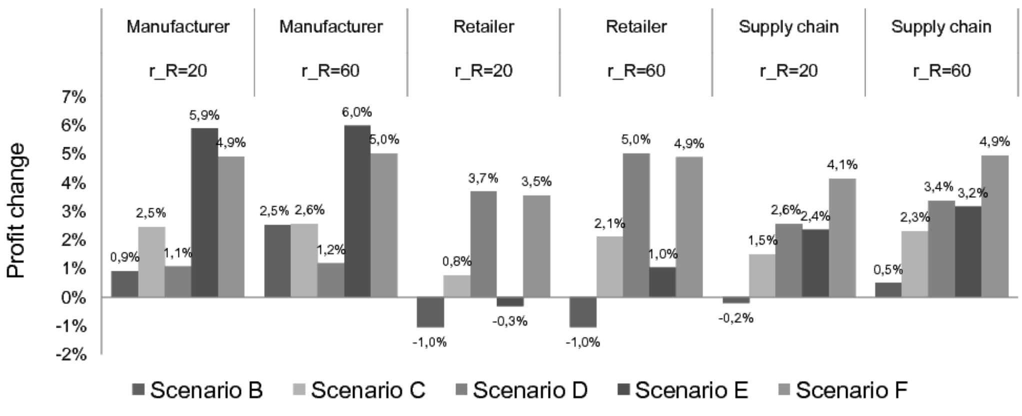


Figure 2.10: Sensitivity of the relative profit changes with respect to the unit sales price r_R

changes of the retail price r_R are almost negligible in scenarios C-F. Only in

scenario B, i.e. the scenario where the manufacturer uses RFID unilaterally and prevents usage on the retail side, the profit of the manufacturer is significantly affected by varying product prices. This is due to the fact that the difference between the manufacturer's absolute profit levels achieved in the scenarios A and B is quite small and a change of the product price therefore has a more significant effect.
Figure 2.10 also shows that a change of the product price has a positive impact on the retailer's profit from using RFID in all cooperative scenarios. Only in scenario B where the retailer cannot use RFID, a change of the product price has no effect. The impact of r_R is intuitive since the retailer's ability to sell more products and charge the manufacturer for under deliveries becomes is more valuable if the corresponding benefits are higher in absolute terms.
The positive effect of the product price on the retailer's relative profit gains in scenarios C, D, E, and F and the positive effect on the manufacturer's relative profit in scenario B leads to an increasing percentage gain of the entire supply chain from RFID usage.

Figure 2.11 demonstrates the impact that a change of the percentage retail markup m_R has on the value of RFID in the considered scenarios. For

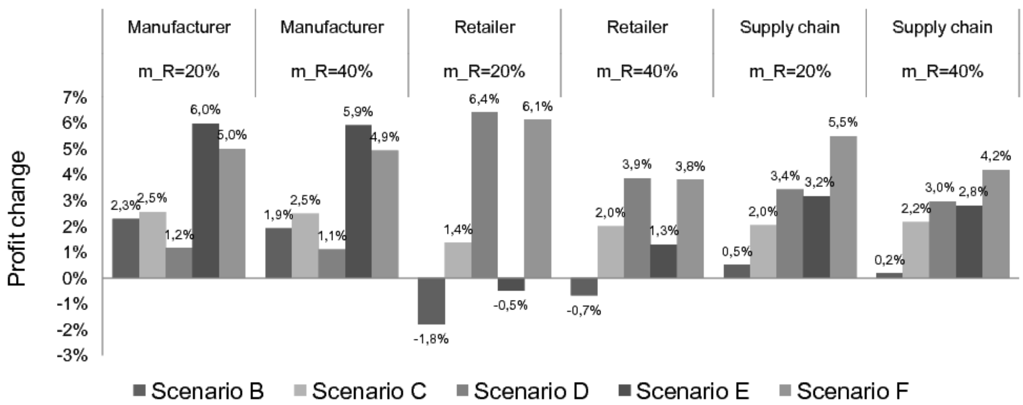


Figure 2.11: Sensitivity of the relative profit changes with respect to the percentage retail markup m_R

the manufacturer, a change of m_R has only marginal consequences. A change of m_R simply shifts the absolute values of the unit revenue and production cost. Therefore the impact of m_R on the manufacturer's percentage profit gains in the scenarios C to F is rather limited.
Compared to its effect on the manufacturer, a change of m_R has a significant

impact on the retailer's profit change resulting from RFID usage. As Figure 2.11 shows, higher percentage retail markups lead to significantly lower percentage profit increases in scenarios D and F, i.e. if the retailer realizes additional value from applying the RFID-based compensation policy (scenario D) or benefits from the complete elimination of errors (scenario F). On the other hand, higher values of m_R lead to higher relative retailer profits in the remaining scenarios (B, C, and E). The explanation of this result is that higher values of m_R reduce the relative importance of the wholesale price $(1 - m_R)r_R$ and therefore the value that can be saved by applying the compensation policy or achieving accurate delivery. In scenarios C and E an increase of the retail markup amplifies the positive effect of the increased fill rate at the stores whereas it reduces the weight of the additional value obtained by applying the RFID-based compensation policy (scenario D) or benefits from the complete elimination of errors (scenario F). In scenario B the under deliveries of the manufacturer cause less stock-outs since m_R has a positive influence on the order quantity.
The sensitivity of the percentage profit improvement of the entire supply chain with respect to the percentage retail markup is much less pronounced than the retailer's profit improvement. This is due to the fact that increasing m_R leads to a higher importance of the retailer's profit in the total supply chain profit equation.

Figure 2.12 reveals the impact of changes to the percentage supplier markup m_M on the relative profit changes resulting from RFID usage. Higher values

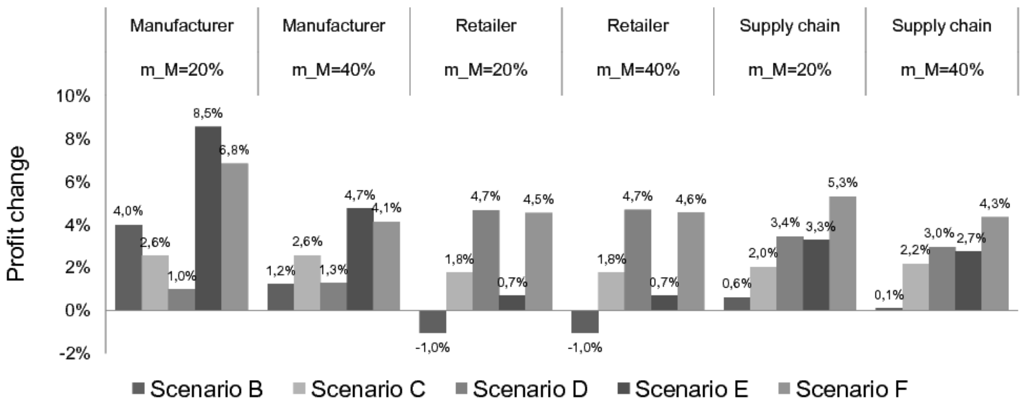


Figure 2.12: Sensitivity of the relative profit changes with respect to percentage supplier markup m_M

of m_M lead to a decrease of the manufacturer's profit from RFID usage in scenario B. This is due to the fact that the production cost savings have a

higher weight if the manufacturer's margin is lower. The same effect can be observed in the scenarios E and F where the manufacturer also uses RFID to save production cost. In the remaining scenarios C and D the manufacturer's markup has no significant effect on her profit since RFID is not used to prevent over deliveries or to observe shrinkage.
The retailer's profit from RFID usage in the different scenarios is not significantly affected by m_M. This result directly follows from the profit functions provided in Section 2.3.6 since m_M does not appear in any of them.
Regarding the total supply chain profit, m_M influences the percentage improvements in the expected way. In all scenarios where the manufacturer's profit decreases, the corresponding supply chain profit decreases and vice versa. Similar to the sensitivity with respect to m_R, the percentage impact on the manufacturer side is much higher compared to the changes on the supply chain level because the relative importance of the manufacturer's profits is lower at lower values of m_M.

Figure 2.13 shows how the factor h that determines the unit salvage value (2.1) affects the relative value of RFID in the different usage scenarios. Different values of h have no significant effect on neither the manufacturer's

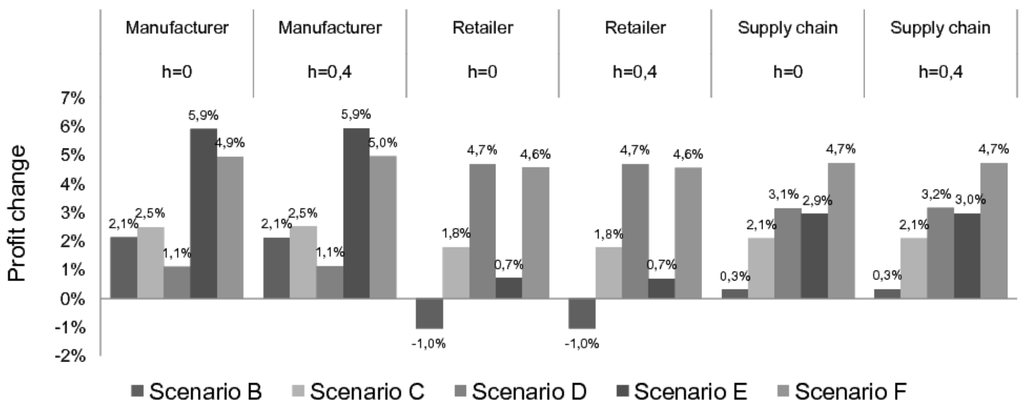


Figure 2.13: Sensitivity of the relative profit changes with respect to the factor h that determines the salvage value

nor the retailer's gains from RFID. Although h has an indirect effect on the absolute profit levels via the order quantity (cf. 2.3 and 2.5), its impact on the relative profit and thus the relative gains resulting from RFID usage are not significant because the relationship of benefits and costs does not change.

Figure 2.14 shows how the RFID transponder cost t affects the profit changes resulting from RFID usage. The observable impact of t on the percentage

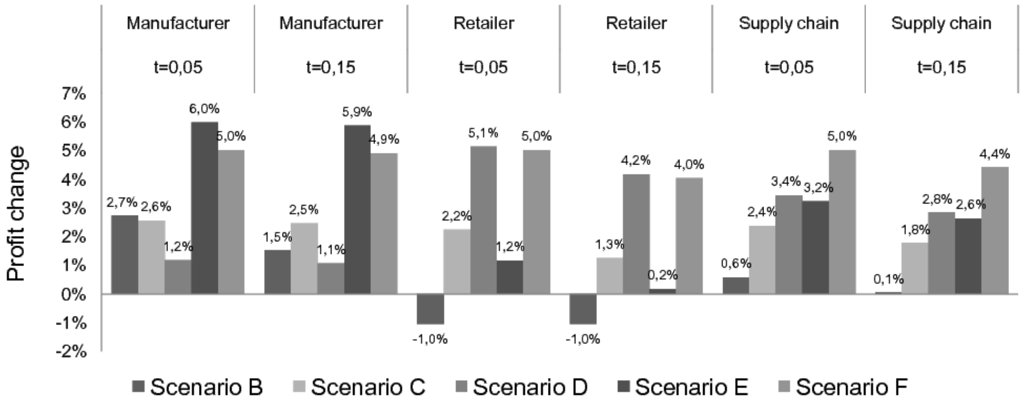


Figure 2.14: Sensitivity of the relative profit changes with respect to the RFID transponder cost t

profit increase is straightforward. Whoever incurs the tagging cost, i.e. the manufacturer in scenario B and the retailer in the scenarios C, D, E, and F, has a lower absolute profit in the RFID usage scenarios. As a consequence, the impact of RFID on the manufacturer's profit remains almost constant in all scenarios except scenario B. The retailer's profit gains are significantly affected in all scenarios except scenario B. From the results presented in Figure 2.14 it can be followed that the cooperative use of RFID (scenarios C to F) remains profitable even at a relatively high unit tagging cost.

Figure 2.15 reveals the influence of mean consumer demand on the impact of RFID in the different scenarios. The mean demand level, similar to the

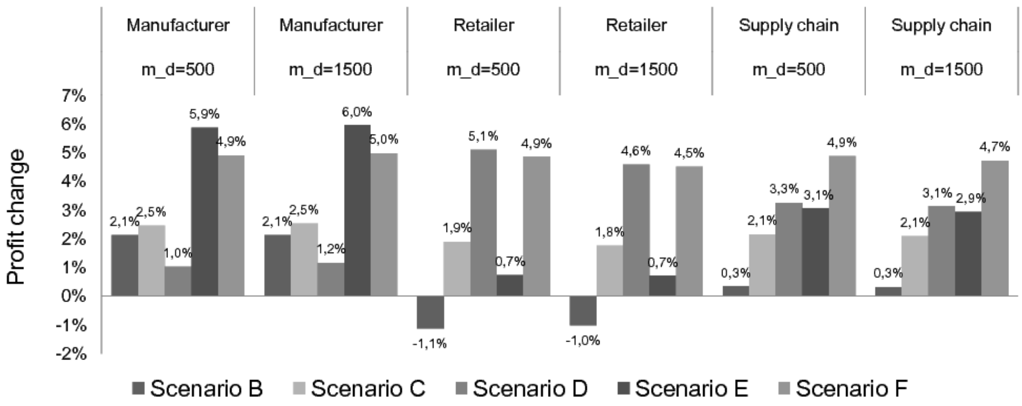


Figure 2.15: Sensitivity of the percentage profit improvements with respect to the mean customer demand μ_d

salvage value factor h, has a minor effect on the both the manufacturer's and the retailer's profit changes resulting from the use of RFID. This outcome can be explained by the fact that μ_d has an overarching effect on the absolute profits along the supply chain. As one of the parameters of the demand distribution it determines the order quantity and the degree of delivery error. A higher level of the mean demand causes the order size and thus the absolute profit levels in the status quo and the different RFID usage scenarios to increase but preserves their relationships, i.e. the profit in scenario A increases by the same relative amount as the profit in the remaining scenarios.

Figure 2.16 reveals the influence of the standard deviation of the consumer demand on the impact of RFID. The impact of the demand variance on the

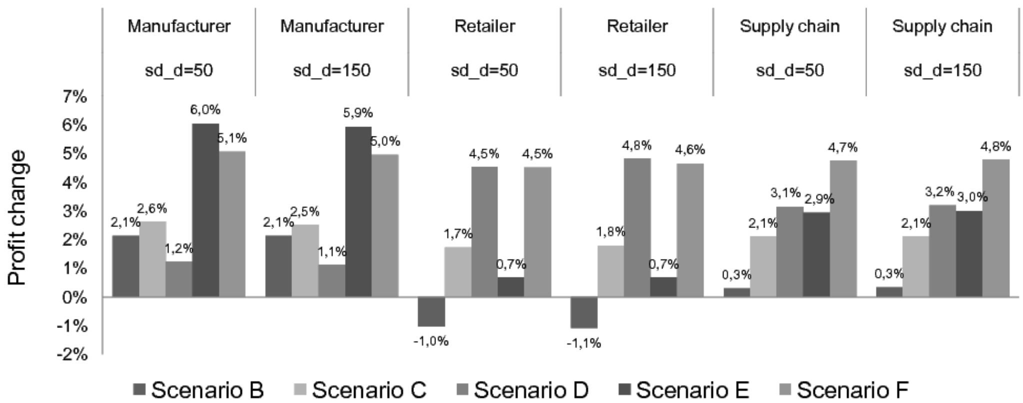


Figure 2.16: Sensitivity of the relative profit changes with respect to the standard deviation σ_d of the customer demand

profit changes is very small. Similar to h and μ_d it influences the order quantity and therefore all profit levels at the same time without changing their relationships.

Figure 2.17 shows the influence of different levels of store efficiency in the status quo. The parameter α determines the degree of store inefficiency in the status quo. It therefore has a positive impact on the manufacturer's value from using RFID in all cooperative RFID usage scenarios. This is due to the fact that more products can be sold in those scenarios compared to the status quo and thus the absolute profit of the manufacturer is higher. The impact of lower store efficiency in the status quo has the same effect on the retailer. The absolute profit levels resulting from RFID usage in the cooperative scenarios C, D, E, and F are higher because RFID helps to increase sales. If the manufacturer does not cooperate with the retailer

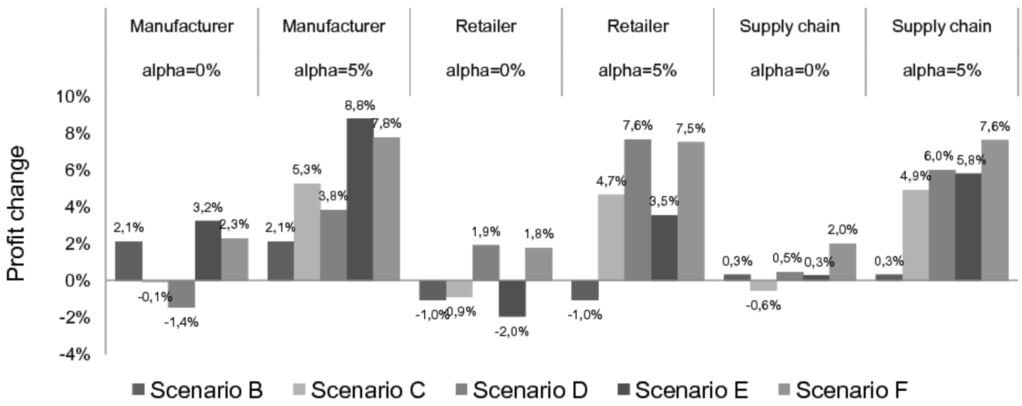


Figure 2.17: Sensitivity of the relative profit changes with respect to the factor α that determines the loss of demand due to inefficient store processes

regarding RFID, α has no effect since RFID cannot be used in the retailer's stores then.
On the supply chain level, α has a positive effect on the percentage profit improvements due to RFID in all cooperative scenarios.

In summary, the sensitivity analysis shows that the general results obtained in Sections 2.4.2 and 2.4.2 and in particular the Results 1, 2, 3, and 4 do not depend on any of the input parameters.

2.5 Strategic Implications

In this section we analyze the strategic implications of the results presented in the two preceding sections. In particular, we predict the degree of item-level RFID usage in the supply chain by applying basic tools from game theory. Game theory mainly deals with the emergence of strategic equilibria based on the assumption that rational subjects in an economy, such as the companies forming part of a supply chain, choose their actions not only based on information about themselves but also based on the expected actions and profits of other players.
Considering the strategic interaction of stake holders is crucial since in many real world situations the decision of one player can influence the utility of another player and vice versa. In the absence of such spill over effects or externalities it suffices to find the maximum profit of a stake holder provided her own action alternatives in order to predict her decision. Game theory uses the concept of dominance to rule out situations where one player is al-

ways better off choosing a particular strategy irrespective of what the other players do. As the previous analysis has revealed, there exist significant spill over effects regarding the deployment of item level RFID along the supply chain. For instance, if the manufacturer does not tag products, the retailer cannot use them to make store operations more efficient.[3] Depending on the current level of store inefficiency, the decision of the manufacturer can thus have a negative impact on the retailer's profit. We speak of negative externalities in this case. The spill over effect can also be observed in the opposite direction, i.e. actions of the retailer can affect the manufacturer's profit. For instance, if the retailer can increase shelf availability by using RFID in her stores, the manufacturer benefits from the higher demand of the retailer. Since the choice of the retailer to use RFID in the stores has a positive impact on the manufacturer's profit, we speak of positive externalities. Another example for a negative externalities is when the manufacturer uses RFID unilaterally for preventing over deliveries. In this case the retailer suffers from the manufacturer's use of the technology. The existence of measurable externalities motivates the game theoretic analysis presented in this section.

In the following we translate the coordination problem of RFID usage along the supply chain into the language of non-cooperative game theory and derive predictions regarding the most likely RFID usage scenario. We assume that the strategic interaction of the manufacturer and the retailer starts in the status quo, i.e. item-level RFID is not used by either of the companies. Furthermore, we begin the analysis by hypothesizing that the retailer is the driving force behind the RFID initiative, i.e. she is first to take action. Regarding the background information about the current state of item level RFID adoption and the benefit perceptions prevailing in practice, this assumption seems more intuitive than the assumption that the manufacturer is first to propose item level tagging.
Furthermore, we assume throughout the game theoretic analysis that both players possess complete information. Complete information in the context of our supply chain model implies that the supplier and the retailer know each others profit functions and options for action regarding the use of RFID. Although this is a very strong assumption, a game theoretic analysis based on full information is a useful first step to understand the strategic implications of RFID usage in supply chains.

[3]We assumed that it does not make economic sense for the retailer to tag products herself.

Before we begin with the actual game theoretic analysis, we provide a number of formal definitions tailored to the RFID usage in supply chains, in particular the notion of non-cooperative equilibria. Games in normal form can be fully characterized by the set of players $N = \{1, 2, ...\}$, the possible strategies of the players $S_i = \{s1_i, s2_i, ...\}$ and the profit of each player i that results from all possible strategy vectors $s \in (S_i)$ (cf. e.g. Osborne [2004]). Using game theoretic notation, the RFID usage game can thus be formally described as follows.

Definition 1 *(RFID usage game)*

The supplier M and the retailer R are the players of the RFID Usage Game. N denotes the set of players, i.e. $N = \{M, R\}$. Their respective utility functions of the players are given by $\Pi_M(s_M, s_R)$ and $\Pi_R(s_M, s_R)$.
The strategy space of player M is $S_M = \{s1_M, s2_M, s3_M, s4_M\}$.
$s1_M$: No RFID
$s2_M$: Attachment and use of incompatible tags in the picking and shipping processes
$s3_M$: Attachment of compatible tags and no use of the tags if player R requests tagging
$s4_M$: Attachment and use of compatible tags in the picking and shipping processes if player R requests tagging
The strategy space of player R is $S_R = \{s1_R, s2_R, s3_R\}$.
$s1_R$: No RFID if player M defects
$s2_R$: Use of compatible tags in the stores if player M cooperates
$s3_R$: Use of compatible tags at the goods receipt and in the stores if player M cooperates
The game can be fully characterized by the tuple $\langle N, S_M, S_R, \Pi_M, \Pi_R \rangle$.

As one can see from the definition of the RFID usage game, the applicability of strategies is interdependent. If player R does not request tagging, the player M can only chose between $s1_M$ and $s2_M$. Thus, if M does not cooperate with respect to RFID tagging, the R cannot chose strategies $s2_R$ and $s2_R$. These interdependencies require a decomposition of the RFID usage game into several subgames. In order to make the analysis of the game more transparent we consider its extensive form in the following analysis. Figure 2.18 shows the extensive form representation of the RFID usage game if the retailer is first to move. As indicated by Figure 2.18, the RFID usage game can be subdivided into three subgames. Subgame 1 is the entire RFID usage game itself. Subgame 2 begins either if the retailer choses not to request tagging, or if the retailer requests tagging but the manufacturer defects. The only player who can make a move in subgame 2 is the manufacturer. She

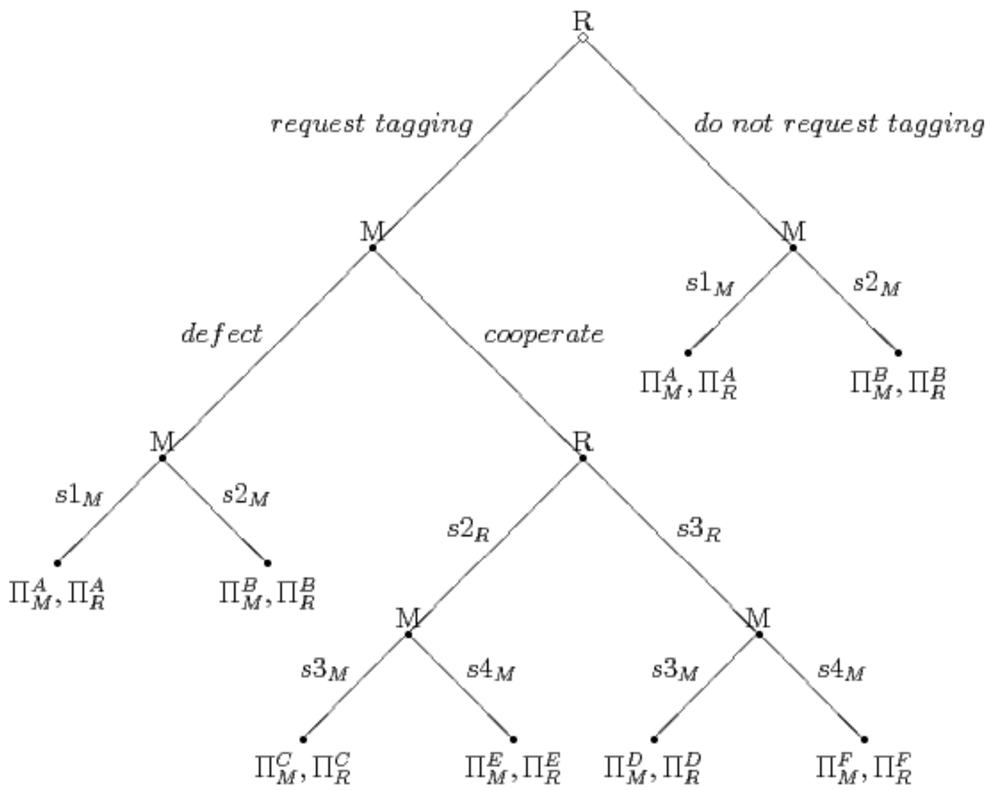


Figure 2.18: Extensive form of RFID usage game if retailer requests tagging

can either chose to strategy $s1_M$ or $s2_M$, i.e. to not use RFID or to use it by herself. Subgame 3 begins after the retailer has requested tagging and the manufacturer has chosen to cooperate. In subgame 3 both the manufacturer and the retailer have two possible strategies to choose from. The manufacturer can chose between $s3_M$ and $s4_M$, and the retailer can either follow strategy $s2_R$ or $s3_R$. The normal forms of the subgames 2 and 3 are provided in Figures 2.19 and 2.20 respectively. The profit functions used

$$
\begin{array}{ccc}
 & & R \\
 & & s1_R \\
\multirow{2}{*}{M} & s1_M & \Pi_M(s1_M, s1_R),\ \Pi_R(s1_M, s1_R) \\
 & s2_M & \Pi_M(s2_M, s1_R),\ \Pi_R(s2_M, s1_R)
\end{array}
$$

Figure 2.19: Normal form of subgame 2 of the RFID usage game

$$
\begin{array}{cccc}
 & & \multicolumn{2}{c}{R} \\
 & & s2_R & s3_R \\
\multirow{2}{*}{M} & s3_M & \Pi_M(s3_M, s2_R),\ \Pi_R(s3_M, s2_R) & \Pi_M(s3_M, s3_R),\ \Pi_R(s3_M, s3_R) \\
 & s4_M & \Pi_M(s4_M, s2_R),\ \Pi_R(s4_M, s2_R) & \Pi_M(s4_M, s3_R),\ \Pi_R(s4_M, s3_R)
\end{array}
$$

Figure 2.20: Normal form of subgame 3 of the RFID usage game

in Definition 1 and Figures 2.19 and 2.20 can be mapped to the scenario profit functions used in the preceding sections as shown in Table 2.3. Given

$\Pi_M(s1_M, s1_R)$	Π_M^A
$\Pi_M(s2_M, s1_R)$	Π_M^B
$\Pi_M(s3_M, s2_R)$	Π_M^C
$\Pi_M(s3_M, s3_R)$	Π_M^D
$\Pi_M(s4_M, s2_R)$	Π_M^E
$\Pi_M(s4_M, s3_R)$	Π_M^F
$\Pi_R(s1_M, s1_R)$	Π_R^A
$\Pi_R(s2_M, s1_R)$	Π_R^B
$\Pi_R(s3_M, s2_R)$	Π_R^C
$\Pi_R(s3_M, s3_R)$	Π_R^D
$\Pi_R(s4_M, s2_R)$	Π_R^E
$\Pi_R(s4_M, s3_R)$	Π_R^F

Table 2.3: Mapping of profit functions

Definition 1 and the mapping of profit functions provided by Table 2.3, the numerical results presented in the Section 2.4 can be used to construct game theoretic arguments.

The subgame perfect equilibria of the RFID usage game can be determined by backward induction (cf. Osborne [2004]). Backward induction works in the following way: first one considers the last actions of the entire game in extensive form and determines which strategy the final mover has to implement in order to maximize her profit. One then supposes that the last mover will implement this strategy, and considers the second last mover, again choosing the strategy that maximize that player's profit. This process continues until one reaches the first move of the game. The remaining strategies are all subgame perfect equilibria.

In order to determine the subgame perfect equilibria of the RFID usage game we carry out backward induction using the extensive form of the game shown in Figure 2.18, the normal forms of the subgames 2 and 3 are provided by Figures 2.19 and 2.20, and the numerical results provided in Section 2.4.2.

To begin with we determine the Nash equilibrium of subgame 2. The formal definition of Nash equilibria is provided in Definition 2.

Definition 2 *(Nash Equilibrium)*

The strategy vector e^{NE} *is a Nash equilibrium of the game* $\langle N, (E_i), (\Pi_i) \rangle$ *if* $\Pi_i(e_i^{NE}, e_{-i}) > \Pi_i(e_i \neq e_i^{NE}, e_{-i})$ *for all players* $i \in N$.

Translated into human language, the outcome of a game is a Nash equilibrium if no player has an incentive to unilaterally deviate from it by choosing a different strategy. Since only the manufacturer has a choice to make in this game, the solution is simple. She will either pick strategy $s1_M$ or $s2_M$ depending on whether $\Pi_M(s1_M, s1_R)$ or $\Pi_M(s2_M, s1_R)$ is higher. The corresponding outcome is the Nash equilibrium subgame 2. Result 1 states that from certain values of (θ_y, θ_y) onwards $\Pi_M^B > \Pi_M^A$ is true and that otherwise the opposite it true. Thus, the Nash equilibrium of subgame 2 depends on the intensity of the delivery error.

Next we determine the Nash equilibrium of subgame 3. It can easily by shown that this approach is equivalent to solving the subgame by backward induction under complete information. Lemmas 2.5.1-2.5.4 provide the formal conditions for scenarios C-F being Nash equilibria of subgame 3 respectively.

Lemma 2.5.1

Outcome $(s3_M, s2_R)$ *is a Nash equilibrium of subgame 3 if the following conditions are fulfilled:*

$\Pi_M^C > \Pi_M^E$

$\Pi_R^C > \Pi_R^D$

Lemma 2.5.2

Outcome $(s3_M, s3_R)$ *is a Nash equilibrium of subgame 3 if the following conditions are fulfilled:*

$\Pi_M^D > \Pi_M^F$

$\Pi_R^D > \Pi_R^C$

Lemma 2.5.3

Outcome $(s4_M, s2_R)$ *is a Nash equilibrium of subgame 3 if the following conditions are fulfilled:*

$\Pi_M^E > \Pi_M^C$

$\Pi_R^E > \Pi_R^F$

Lemma 2.5.4

Outcome $(s4_M, s3_R)$ *is a Nash equilibrium of subgame 3 if the following conditions are fulfilled:*

$\Pi_M^F > \Pi_M^D$

$\Pi_R^F > \Pi_R^E$

Given Results 2 and 4 which state that $\Pi_M^E > \Pi_M^C$, $\Pi_M^F > \Pi_M^D$, and $\Pi_R^F > \Pi_R^E$ for all positive values of θ_y and/or θ_z it can be shown that only the conditions of Lemma 2.5.4 are fulfilled. Thus the unique Nash equilibrium of subgame 3 is outcome $(s4_M, s3_R)$. This result implies that in case the game reaches the point where subgame 3 begins, the manufacturer will seek to completely prevent delivery errors by using RFID technology for monitoring the picking and shipping process and the retailer will use RFID both in her stores and at the goods receipt.

Given the unique Nash equilibrium of subgame 3 the backward induction can continue. If the game reaches the stage at which the manufacturer has to decide whether to cooperate or not, she is can choose to cooperate and obtain a profit of Π_M^F (the unique Nash equilibrium of subgame 3) or to defect and realize a profit of either Π_M^A or Π_M^B (the unique Nash equilibrium of subgame 2). The numerical results presented in Section 2.4.2 show that

Π_M^F is always greater than both Π_M^A and Π_M^B for the considered value ranges. However, as can be inferred from Figures 2.1 and 2.3, Π_M^B steadily increases with increasing levels of θ_y whereas Π_M^F remains constant. Therefore Π_M^B can become greater than Π_M^F if picking errors occur more frequently than considered in the numerical study or if the retailer cannot substantially increase the efficiency of her store processes using RFID (cf. Figure 2.17).

Given the above information we can infer the decision problem of the retailer at the beginning of the RFID usage game. If she decides not to request tagging, the manufacturer can still decide to use RFID unilaterally which is a plausible move if the total delivery error is sufficiently high. This outcome would make the retailer strictly worse off than the status quo if the manufacturer prevents over deliveries resulting from picking errors but permits under deliveries. If she decides to request tagging, she will either realize Π_R^A, Π_R^B, or Π_R^F depending on the relationship of Π_M^A, Π_M^B, and Π_M^F. Provided the knowledge gained from the numerical study, the chances are fairly high that Π_M^F is greater than both Π_M^A and Π_M^B. Hence, by asking the manufacturer to tag products the retailer can add scenario F to the possible outcomes of the RFID usage game. In any event, the retailer has no influence on the realization of scenarios A and B which both represent possible outcomes of the game irrespective of her strategic choice. Since the retailer is strictly better off in scenario F compared to the other possible scenarios, her optimal strategy is to request tagging in the first stage of the RFID usage game.

If the manufacturer is first to move in the RFID usage game, the subgame perfect equilibrium obtained does not differ from the one obtained if the retailer moves first. The game then simply starts at the node where the manufacturer decides to cooperate or to defect.

2.6 Limitations

Our results have to be seen against the background of a number of limitations mentioned in this section.
First of all, we use a model-based approach to analyze the benefits of RFID usage along the supply chain. This model has to be sufficiently simple to conduct a comprehensible and reproducible analysis. Although the single period Newsvendor model is well-established in the operations management literature, its practical relevance is limited to the distribution of goods with short sales periods such as apparel, consumer electronics or perishable goods such as food products. Luckily, as we outlined in the introductory chapter

of this dissertation, the economic benefit of using item-level RFID in the distribution, sale, and after sale of high-impact products is likely to be more positive than its benefit regarding low-impact products. Thus, although the model is not able to adequately describe the distribution processes of all possible types of products, it accurately represents the basic economic trade-offs involved in the distribution of products that are also likely to be tagged first (cf. Chapter 1).

Similar to previous model-based work on RFID value, we do not consider the fixed costs of RFID readers, infrastructure, and further IT investments that are necessary to implement item-level RFID. These costs can be estimated fairly well in practice and do not depend on the other model parameters (unlike the tagging cost). Furthermore, the implemented RFID infrastructure used not only for one type of product, but for all tagged products that move through the supply chain. Thus, the ultimate return on investment resulting from the usage of item-level RFID can be calculated by taking the profit values resulting from our model and comparing these to the estimated fixed costs, e.g. by conducting a net present value analysis.

In order to calculate the benefits obtained from monitoring the supply chain, we had to make a number of assumptions regarding the business conduct of the considered RFID stake holders.
First of all, we assume that the business partners act in their own self-interest and therefore strive to increase their profits even if this means to reduce the profits of the respective business partner. For instance, if the retailer is able to detect under deliveries, we assume that she demands compensation from the manufacturer. In some business environments this assumption may not be justified, for instance because the retailer does not want to strain the business relationship with the manufacturer. If the retailer depends on the products delivered by the manufacturer or if the retailer is indebted to the manufacturer due to some other reason, she may refrain from paying less than the negotiated purchase price just because some items are missing.

Publicly available information about execution errors in different types of supply chains is sparse. Whereas empirical research on store efficiency is increasingly available, the accuracy of picking and delivery operations still seems to be a well-kept secret. In particular the amount of shrinkage due to employee theft is a delicate topic that managers usually try to avoid due to political reasons. Since most of the benefits provided by RFID-based monitoring of the supply chain result from the detection and prevention of errors that cannot be tackled using other practices or technology, it is crucial for companies evaluating RFID to collect reliable data on their likelihood in their individual context. Instead of considering one particular supply chain, we put an emphasis on investigating the general effect of execution errors and provide profitability calculations for ranges of input parameters.

2.7 Conclusions

Item-level RFID has to date been perceived solely as a means to increase store efficiency (cf. e.g. Gaukler et al. [2007]). The manufacturers who have to attach item-level RFID tags in order to make RFID work for the retailers currently seem to perceive RFID tagging as a sunk cost. They are usually more interested in tracking cases or pallets of goods in their distribution centers. RFID tagging on the case/pallet level usually suffices to realize many of the predominantly perceived automation benefits, i.e. the reduction of documentation errors as well as labor and time savings. Thus, if the retailers want to use item-level RFID to improve store processes and do not possess extraordinary power over the manufacturers, they inevitably incur the tagging cost. Provided that retailer pay for item-level RFID tagging, we find it interesting to investigate what makes retailers and manufacturers use RFID-based monitoring other than on the sales floor. According to recent empirical studies on what drives RFID adoption, these economic incentives appear to be the current drivers of supply chain wide RFID usage.

The vision of the industry consortium EPCglobal is to provide supply chains with the capability to track single products from the moment of their production onwards using the RFID technology. On the one hand, this can lead to advances in the area of supply chain control and execution because distribution processes can be monitored in real time as well as retrospectively. On the other hand, it could enable promising applications such as the implementation of more efficient control mechanisms to assure product quality, in particular efficient product authentication, returns and recalls. The RFID technology has now reached a sufficiently high level of maturity making EPCglobal's vision at least technically feasible. Furthermore, RFID and EPC-related technologies have been standardized in recent years and these standards have also been adopted by the majority of RFID vendors.
Despite the recent progress in RFID standardization and the development of scalable back end solutions, the purchase, implementation, and operation of RFID related hard and software still comes at a significant cost. Manufacturers will not start tracking products on the item-level if they obtain no additional benefit from this practice. Even if retailers pay the entire tagging

cost, the manufacturers still have to build and operate RFID infrastructures in order to come closer to EPCglobal's vision of supply chain wide product tracking and tracing. In case they already use RFID on the case or pallet-level, the incremental effort of introducing item-level RFID will of course be smaller but remains significant.

The main research questions treated in this chapter are whether cross-company item-level RFID makes economical sense and how the strategic interaction of the involved stake holders affects its introduction. In order to address these research questions, we propose an economic model that describes the basic economic trade-offs determining the interaction of a manufacturer and a retailer forming part of the same supply chain. Based on this model we numerically demonstrate the impact of three types of execution errors: Errors in the picking process, shrinkage in the supply chain, and inefficient store processes. By assuming that item-level RFID will eliminate those inefficiencies, we are able to calculate the profits of the manufacturer and the retailer under different model assumptions. We find that the deployment of item-level RFID results in externalities, i.e. its deployment at the manufacturer has quantifiable consequences on the retailer and vice versa. The existence of these externalities necessitates the application of game theory in order to understand the strategic implications of item-level RFID usage along the supply chain. In particular, using the results of our numerical study, we predict possible outcomes of the resulting RFID usage game. Provided that our assumptions regarding the degree of execution errors and the impact of RFID are correct, the most likely outcome of the strategic interaction is the usage of item-level RFID along the supply chain in order to not only observe but prevent execution errors. Although there exist parameter configurations for which our game theoretic model predicts a different outcome, in particular the unilateral and uncooperative use of RFID by the manufacturer, the probability that these configurations exist in reality is relatively small.

According to our results, the emergence of the predicted strategic RFID usage equilibrium would lead to a significant increase of the individual profits of both the manufacturer and the retailer. Moreover, it would result in no obvious incentive restrictions regarding RFID data sharing practices. Both, the deployment of standardized RFID infrastructures along the supply chain and the non-existence of economic incentives for hiding proprietary information about the movement of products are preconditions of the eventual realization of EPCglobal's vision.

Chapter 3

The Value of Item-Level RFID in the Retail Store

3.1 Introduction

The provision of high product availability at minimal operational costs is a key success factor in the retail industry. If competition is fierce and profit margins thin, the ability of distribution systems to provide the "right" amount of stock at the "right" place becomes even more important. In order to increase their logistical performance, most companies have automated their inventory management processes to better meet customer demand and reduce costs. For instance, many retailers nowadays use decision support systems that advises store personnel when to restock shelves or even places orders with their suppliers automatically. On the one hand, the use of advanced IT systems in retail reduces human intervention thereby saves expensive working hours and rules out human error. On the other hand, it improves the retailer's ability to keep track of an ever increasing number of stock keeping units (SKUs) and initiate replenishments early enough to prevent stock-outs and the resulting loss of revenue. However, by the increasing use of fully automated stock management systems retailers also become more dependent on them. In order to prevent serious consequences, they have to make sure that all necessary conditions for their flawless working are met. In particular, the use of automated inventory control requires accurate information regarding which products are where in what quantity. If the data provided to the automatic inventory management system is incorrect or outdated, the ability of the system to support or even automate decision making is compromised. Thus, the focus of many retailers has recently moved from automating "back end" decision making to increasing the quality of the data stored in their

data bases or even collect more data on the sales floor. Being able to collect more data can enable retailers to satisfy consumer demand more efficiently. Apart from using Point of Sale (POS) data for planning purposes such as shop layout and long term supply management, real time data on the location of items on the sales floor can help to increase store execution. Not surprisingly, the inventory management system is not able to provide exact guidance when to put which product from the back room to the shelves if it has no information about the location of products in the store. Instead, the store personnel has to rely on visual judgment and experience to refill shelves as efficiently as possible. Furthermore, if the IT system's stock record for a product does not agree with the actual inventory left at the store, orders with the supplier may not be placed in time; or the facility could carry more inventory than is necessary to meet consumer demand.
Despite the progress that has been made regarding the use of automated decision making in inventory control settings, the fundamental task of assuring a sufficient level of data quality to make the approach work as expected remains challenging. Achieving higher data quality and reducing data capturing cost are the main reason why major retailing companies, including Wal-Mart and Target in the US, Tesco in the UK, and Metro in Germany, have begun to roll out RFID systems at the case and pallet-level. At least Wal-Mart has also fixed a deadline for item-level compliance with its suppliers (cf. Weier [2008]). However, provided that case and pallet-level RFID has still not been adopted by many of its suppliers, it is questionable whether this deadline will actually take effect. Furthermore, Wal-Marts item-level RFID mandate actually refers to the sellable unit level at its Sam's Club stores. According to Burnell [2008], "many products sold at Sam's Club are only available in multi-packs or bulk, so tagging at the sellable-unit level does not necessarily require tagging each item within the package". Due to its size, Wal-Mart possesses significant market power which can be used to pass on the tagging cost to its suppliers. However, due to the high cost of item-level versus pallet-level RFID, even Wal-Mart will have problems to enforce item-level tagging without sharing costs or benefits. Other companies, especially retailers of apparel and consumer electronics, have also announced plans to introduce item-level RFID. Companies that have already conducted pilot studies to investigate the value of item level RFID include American Apparel (cf. Gaudin [2008]) and Dillard's (cf. O'Connor [2007]) in the US and Karstadt (cf. Heise Online [2007]), Galeria Kaufhof (cf. Wessel [2007]), Gerry Weber (cf. Goebel et al. [2009c]) and others in Europe. Most of them do not possess similar market power as Wal-Mart and therefore have to be sure that their investment into item-level RFID pays off. American Apparel's RFID project manager claimed that "as many as 10% of items that should

be on the sales floor could be missing at any given time. Sales increase by 15% to 25% when all items are available on the floor. The RFID system has made 99% of sales floor inventory available to customers" (Gaudin [2008]). Provided these figures, however, one has to consider the particular circumstances in American Apparel stores. In fact, they have implemented a sales strategy that requires not more than one item per SKU being available on the sales floor which increases their dependency on the efficiency of the shelf restocking process. Moreover, they make their own products, which prevents the usual coordination issues with manufacturers that are requested to tag products but see little benefit in item-level tagging (cf. Chapter 2).

The focus of the work presented in this chapter lies the methods that can be applied to measure the value of full inventory visibly in prototypical retail stores. As we outlined in the introductory chapter of this dissertation, the uncertainty among companies regarding the value of RFID still prevents its adoption in many cases. In cases where the benefit of implementing an RFID based solution significantly exceeds the corresponding cost, a failure to adopt RFID leads to opportunity costs. In order to prevent these opportunity costs, more accurate and reliable methods for estimating RFID benefits are needed.

Many publicly accessible tools for estimating RFID's return on investment (ROI) offer ready-made spreadsheet frameworks for estimating RFID's impact on operational costs, in particular time savings resulting from the replacement of traditional bar codes (cf. e.g. IBM and GS1 [2004]). The value of the additional visibility that RFID can provide has to date been less emphasized although practitioners slowly begin to acknowledge its value. For instance, the manager in charge of American Apparel's pilot stated that "at the pilot store, we used to have to hand count items on the sales floor twice a week to keep the inventory accurate. Now we're doing it once a month. This visibility and granularity is really going to benefit the company even more than reduced labor and costs" Gaudin [2008]. In fact, in retail settings with relatively high unit margins such as apparel, increasing sales by 10% as quoted by American Apparel managers is worth significantly more than a few hours of labor saved at the goods receipt every month. Explanations for the fact that stock visibility is often not considered in RFID value calculations are manifold. On the one hand, inventory inaccuracy and lost sales resulting from stock out cannot be directly observed and thus store managers are sometimes unwilling to use them as qualified input for ROI calculations. Some reasons for inventory inaccuracy, in particular employee theft, are political and are often avoided by managers. On the other hand, measuring the value of information requires more sophisticated methods than determining labor cost savings resulting from higher counting efficiency. In particular, a sufficiently realistic model of how information is transformed into decisions and how these decisions affect the financial performance of retail stores is needed.

In section 3.2 we review the academic and non-academic literature relevant to the research presented in this chapter. Section 3.3 provides an overview of the model we use to capture the information value of RFID in retail operations. In Section 3.4 we present and analyze the results obtained from a simulation study based on the model defined in Section 3.3. Section 3.6 concludes the research presented in this chapter.

3.2 Related Work

Recent empirical work has documented the lack of inventory accuracy in retail environments. For instance, DeHoratius and Raman [2008] found that the inventory records of 65% of the SKUs stocked by one retailer were inaccurate. Kang and Gershwin [2005], who investigated the accuracy of system inventory levels at the stores of a global retailing company reported that on average only 51% of the inventory levels were accurate. The best performing store in their sample had only 70-75% of its inventory record matching the physical inventory at the date of the yearly audit. In another study, Raman et al. [2003] found that 35-65% of the inventory records at the two retail stores whose data they could analyze were inaccurate. According to the authors, the observed inventory inaccuracies could have the potential of reducing the retailer's profit by as much as 10% due to higher inventory cost and lost sales.

One of the major causes of inventory discrepancy is shrinkage (cf. Atali et al. [2006]). According to industry reports its amount is significant in practice. For example, Alexander et al. [2002] have estimated that the rate of inventory shrinkage amounts to 1.8%, 1.75%, and 1.73% of 2001 sales in the US, Europe and Australasia, respectively.

So-called "phantom stock-outs" represent another reason for decreased store performance. They occur because inventory was stored in places not accessible to the customers. Ton and Raman [2004] estimated that every sixth person who approached a sales person at Borders (a large US based media store) for help with finding a particular product, failed to obtain it although it was actually available at the store. Ton and Raman [2004] also cited a study conducted by Andersen Consulting showing lost sales of US supermarkets that result from phantom stock-outs range at $560-960 million per year. Gruen et al. [2002] who collected and synthesized information from various sources found that phantom stockouts contribute to roughly 25% of stock-outs. Another 13% of the stock-outs are due to inefficient store replenishment processes.

There exist a number of ways to reduce inventory inaccuracy and improve replenishment practices within retail stores on the organizational level (e.g. by increasing the frequency of manual stock counts or by implementing best practices in the area of supply chain and category management). However, as Gruen et al. [2002] have revealed, out of stock levels have not significantly decreased over the last three decades. Most retailers still report average stock out levels ranging between 5 and 10%. According to Tellkamp et al. [2006] this result is rather surprising in view of numerous initiatives on supply chain and category management launched in recent years. It seems that the limits of efficiency on the current level of technology use in retail have been reached. One could thus argue that monitoring single products using RFID is the only way to further increase product availability.

The consensus in practice that many of the persisting inefficiencies in retail operations stem from a lack of inventory visibility have lead to a growing literature in inventory control under imperfect information.
A recent paper dealing with the impacts of inventory inaccuracy due to shrinkage is Kang and Gershwin [2005]. The authors first use a deterministic model to show the impact of inventory inaccuracy on the occurrence of stock-outs in a retail store. Afterwards they also conduct a simulation analysis to investigate the impact of inventory errors in a situation where both demand and shrinkage occur randomly. In both cases the authors show that small departures of the actual from the observed stock levels can already lead to significant stock-out rates.
Atali et al. [2006] compute the effect of three sources of inventory inaccuracy: Misplacement, shrinkage, and transaction errors. They develop a highly complex inventory policy based on dynamic programming which can incorporate statistical knowledge about the distribution of all three types of error. The authors show that using such an "informed" policy is almost as profitable as using RFID. Although the assumption that retailers know the distribution of errors sources is rather unrealistic, the applied mathematical rigor set their work apart from other recent work in this area.
DeHoratius et al. [2005] consider "intelligent" inventory management tools that account for inventory inaccuracy using a Bayesian inventory record. Their inventory management policy is able to infer information about the actual inventory level using replenishment observations and past sales.

Fleisch and Tellkamp [2004] use a simulation approach to estimate the impact of different error sources along the retail supply chain.
Gaukler et al. [2007] use the Newsvendor model introduced in Chapter 2 of this dissertation to demonstrate the effect of inefficient shelf restocking processes on the performance of retailers. Since the classical Newsvendor model does not consider continuous replenishments, the order decision is not affected by inventory errors.
For an extensive review of inventory record inaccuracy and the value of RFID, see Lee and Özer [2007].

We address the need for more comprehensive and accurate RFID evaluation methods in the retail environment by proposing and demonstrating a simulation-based approach. In contrast to previous work, the proposed approach is able to capture both the impact of item-level RFID on the shelf restocking process that takes place inside the store and the process responsible for replenishing the back room stock. Thus, this work differs from the cited literature which either considers only the store replenishment process such as Kang and Gershwin [2005] and Atali et al. [2006], or only the shelf replenishment process like Gaukler et al. [2008]. The flexibility of the simulation based approach also allows for revealing the impact of an array of typical environmental variables on the value of visibility and RFID. Following the main theme of this dissertation, we compute the value of RFID based on the characteristics of high-impact product rather than low-impact ones which also sets our work apart from earlier work in this field.

3.3 The Model

3.3.1 General Assumptions

In order to demonstrate the value of item-level RFID in the retail store, we have developed a simplified model of a single retail store. We assume that the product stock of the store is replenished on a continuous basis, e.g. from an upstream distribution center. Continuous replenishment implies that the product life time is rather long. Thus, holding all products destined for sale in the entire sales period is not possible due to the limited size of storing capacity in the store's back room. In the apparel industry, networks of small stores selling a particular brand are expanding at a fast pace, while traditional department stores are loosing ground (cf. e.g. Ferdows et al. [2004], Goebel et al. [2009a]).

We assume that the retailer sells the product to the end customers at price of r_R Euros. Her profit per unit sold is $r_R - c_R$ Euros where c_R Euros is the purchase cost. Thus, the retailer's relative markup is $m_R = (r_R - c_R)/r_R$. If a customer does not find the product at its usual place, the retailer incurs a lost sale. Thus, the penalty for every lost sale amounts to $m_R r_R$. Since we consider a retail environment, the lost sale assumption is more reasonable than its alternative, the backordering assumption.[1] The penalty for ordering too much is expressed as the holding cost that accrues while the products are waiting to be sold to the end consumer. The daily holding cost is $h_i(1-m_R)r_R/n$ where h_i is the yearly holding cost factor and n the number of days per year.

We assume that orders with the distribution center can be placed each day. Whenever the stock level of the product at the store (back room stock plus products displayed on the sales floor) falls short of a previously determined reorder point, an order of fixed size Q is placed with the upstream distribution center. The reorder point is assumed to be optimal provided the information on consumer demand and store operations that is available. In practice it is often obtained by the use of numerical algorithms or simulations based on the distribution of demand which is estimated based on historical sales data. We assume that the amount of product available in the distribution center is sufficient to fill store orders of arbitrary size at any time. Shipments from the distribution center arrive at the retail store L days after the corresponding order has been placed. After a shipment has arrived, it is added to the back room stock of the store from where it can be used to fill the shelves on the sales floor.

3.3.2 Consideration of Data Quality

If the information about the stock levels in the back room and on the sales floor is complete and accurate, the application of optimal replenishment policies maximizes the retailer's profit. However, the empirical studies cited in Section 3.2 show that this is not the case in practice. Thus, even replenishment policies that are theoretically optimal cannot prevent that poor data quality affects the performance of the retail stores. Most inventory policies applied in practice depend on the ability to monitor the current stock level of different products in order to determine the optimal time of replenishments. Departures of the inventory levels indicated by the store's information system

[1] Backordering would imply that the customer is willing to wait for the product and that the retailer may incur a monetary penalty corresponding to the waiting time.

and the actual stock levels can thus have an influence on the store's effectiveness in satisfying customer demand.[2] Thus, even if optimal reorder points and in store shelf replenishment schedules are available, their application to "wrong" inventory data will inevitably lead to sub-optimal performance.

Discrepancies in inventory records can result from various causes in practice. A terms that summarizes a number of these causes is shrinkage. It refers to demand that does not show up in the sales record. In practice, shrinkage is rarely considered because it is hard to monitor in a continuous manner. One example for non-captured demand is theft (from the back room as well as from the shop floor). Furthermore, damage to products on the sales floor or the back room is often not recorded before the damaged products are disposed of. Moreover, if the products on display in the store are time-sensitive in some way, they may be removed from the back room or the shelves after their selling time has expired without indication to the store management system. All described instances of shrinkage leads to a negative departure of the actual inventory level from system inventory.

Another source of inventory inaccuracy are transaction errors. The most commonly cited example is when a customer buys multiple flavors of a product which are all the same price, and the checkout person scans one item and hits the number key to record that multiple units of the same item have been purchased. In this case, the physical stock level of the scanned item will be greater than the system inventory after the scan whereas the actual stock of the products that have not been scanned will have a lower physical inventory level. Scanning error could also be in the form of having the wrong item code recorded, which again would result in a discrepancy between actual and recorded inventory.

Inventory inaccuracy due to shrinkage and transaction errors will remain undiscovered by the system until system and the physical inventories are compared by counting the number of products that are actually available and usable. In practice this usually occurs when inventory audits are conducted. Depending on the individual case, inventory counting may be done just to comply with legal requirements or more often in order to increase the accuracy of stock levels. Either way, I assume that the only economically efficient way to assure that the system inventory level never departs from the

[2] Other types of inventory control policy, in particular policies that are based on time instead of observed inventory levels are not considered here because their relevance in practices is rather low.

actual inventory level, both on the shop floor and in the back room, is the use of item-level RFID in the store.

Misplacement occur when goods have been placed in locations that are not accessible to customers which can lead to the so-called phantom stock-outs. The most common type of misplacement is when the product requested by the customer is available in the back room but not on the sales floor (also referred to as "phantom stock-out"). Another frequently cited type of misplacement occurs when products are available on the sales floor but reside in a location where the customer (and the sales personnel) cannot find it without searching the entire store. A typical type of misplacement specific to the apparel store setting occurs when customers take items to the changing room in order to try them on. Poor stock availability resulting from misplacements may either be due to the complete lack of IT support for shelf management tasks. In this case the store personnel has to rely on their own ability to spot and react to misplacements. or there is a dedicated IT system in place that helps sales staff to identify and resolve misplacements but the data available to this system is incomplete or of poor quality. In practice the only available data is often the restocking schedule and the check-out data which does not suffice to identify stock-outs resulting from misplacements. Either way, shelf management will be less efficient and the resulting lower product availability may have a negative impact on store profit. We assume that RFID, by allowing for "smarter" shelf restocking from the back room and timely identification of misplacements on the sales floor, eliminates lost sales due to misplacements. This assumption is backed by recent pilot studies, e.g. the one conducted by American Apparel (cf. Gaudin [2008]). The cost of purchasing and implementing an RFID-based store management system, however, is deliberately not part of this model.

In the following we describe how shrinkage, transaction errors and misplacements are considered in the model.
The total daily demand d_{total} encompasses the fraction of demand that gets satisfied and paid for by customers d_{pay}, the fraction that shrinks during the day d_{shr}, and the fraction of demand that cannot be satisfied due to misplacements d_{mis}. The "true" daily paying customer demand d_{tru} is the sum of d_{pay} and d_{mis}, i.e. the demand that could be satisfied if the shelves were always filled. Thus paying customer demand d_{pay}, the shrinkage d_{shr}, and demand lost due to misplacements d_{mis} all depend on the realization of the total demand d_{tot}. The random variable d_{total} is assumed to follow a Negative Binomial distribution $NB(\gamma, p)$. If the mean of the total demand is $\mu_{d_{total}}$,

the parameter p of NB can be computed using the following formula.

$$p = \gamma/(\mu_{d_{total}} + \gamma) \tag{3.1}$$

According to Law [2007], the Negative Binomial distribution can be used as a model for demand since it is only defined for positive values. In contrast to the Poisson distribution that has a fixed variance for a given mean, the Negative Binomial distribution can have different degrees of variance for the same mean. The degree of variance of the total demand d_{total} can be controlled by defining the parameter γ of NB. At high levels of γ NB converges to the Poisson distribution with parameter $\mu_{d_{total}}$. For small values of γ, the variance of NB is significantly higher than $\mu_{d_{total}}$.

According to Lee and Özer [2007] transaction errors can be modeled as a separate random variable that does not depend on the total demand. Following Atali et al. [2006] we assume that transaction errors occur according to a Normal distribution with zero mean and standard deviation σ.

In order to determine what happens to the products once they have been received by the store, the model needs to keep track of two different types of inventory levels: (i) the physical inventory level I_{phy} which reflects the total amount product of the considered type that is actually stored in the back room and on the sales floor of the store, and (ii) the virtual inventory level I_{vir} which represents the total product stock as indicated by the store's information system. We assume that the time between subsequent inventory audit intervals is t_{aud} days. After each inventory audit the virtual inventory level I_{vir} is set back to the determined physical inventory level I_{phy}.

The events during the day occur in the following order.

1. The store receives outstanding shipments from the distribution center.

2. Daily demand occurs.

   (a) The occurred paying customer demand d_{pay} gets satisfied if possible and reduces both the virtual inventory I_{vir} and the physical inventory I_{phy} by the corresponding amount.

   (b) The fraction of the true demand that could not be satisfied due to misplacements d_{mis} is lost.

   (c) The shrinkage d_{shr} reduces only the physical inventory I_{phy} by the corresponding amount as long as $I_{phy} > 0$.

(d) Transaction errors that occur during the day augment or decrement the virtual inventory level I_{vir} by the corresponding amount as long as $I_{vir} > 0$.

3. If the time between subsequent audit intervals Δ_{aud} has elapsed, an inventory audit is conducted, i.e. $I_{vir} := I_{phy}$.

4. If the virtual inventory level I_{vir} falls short of the previously determined reorder point R, an order of size Q is placed with the distribution center which arrives after a lead time of L days.

5. The store incurs the inventory holding cost corresponding to the current physical inventory level and lost sale cost corresponding to the fraction of the true demand d_{tru} that could not be satisfied during the day.

In order to assess the value of information about the actual physical inventory level and the current position of products in the back room and on the sales floor, we compare three scenarios denoted by S_{noRFID}, S_{info} and S_{RFID}. In scenario S_{noRFID} RFID is not used and the retailer has no statistical information about the different types of errors considered in this work. In scenario S_{info} the retailer does not use RFID but is able to obtain accurate statistical information on the occurrence of errors. Finally, in scenario S_{RFID} RFID is used to track products in the back room and on the shop floor.
If RFID is not used, the timing of orders being placed with the distribution center is determined based on possibly inaccurate virtual inventory levels and the shelf replenishment suffers from inefficiencies due to the inability to locate products in the back room and on the sales floor. Furthermore we assume that the reorder point is calculated based on historical sales data which can be used to infer the true demand d_{true}.
If the retailer is able to obtain accurate statistical information about the impact of shrinkage and transaction error on the inventory levels and is aware of the exact level of shelf replenishment efficiency, she can use this information in determining the reorder point of the inventory management policy. Statistical information about the distribution of errors may be inferred from audit data or even by sporadically tagging products and monitoring their movements in selected stores. Although these are no realistic assumptions, we include the corresponding scenario into our analysis.
In scenarios S_{noRFID} the estimated true demand is different from the one in scenario S_{RFID} and thus the reorder point calculated based on the historical sales data is different. In scenario S_{info} the calculated reorder point is similar to the one in scenario S_{RFID} since it takes the occurrence of errors into account. However, since RFID is still not used in the actual operation of the

store, inventory inaccuracy persists and the replenishment process remains on the same efficiency level.[3] Hence the application of the informed policy should perform better but cannot outperform the use of RFID.

3.4 Numerical Study

3.4.1 Experimental Setup

We have implemented the model described in Section 3.3 in the programming language Java. Realizations of random were generated according to the model specifications using the SSJ library for stochastic simulation Université de Montréal [2009]. In order to analyze how the different model parameters impact the financial performance of the store we used a factorial design. The value ranges covered by the simulation are provided in Table 3.1. We have chosen parameter ranges that are suitable to describe the properties of rather high-impact consumer products like apparel, footwear, books, CDs, DVDs, toys, etc. Those products are usually stored in large quantities in the distribution center of the retailer and distributed to stores on a continuous basis.

We focus on rather high priced products which is reflected by the considered retail price range (20 to 60 Euros). this price range includes typical high-value consumer products, e.g. DVDs, books, jeans, shirts, MP3 players, memory sticks, etc.

The relatively high retail markups we use as input to the simulation model are also due to our product focus. Most high-impact products have rather high markups because there are few or no exact substitutes available during their life cycles.

Since the average unit RFID tag price was about 5 Eurocents at the time this dissertation was written, the value range of the parameter t should reflect the possible tagging cost now and in the near future relatively well. We assume that RFID tagging is done at the manufacturer's site using automatic tagging equipment.

The chosen range of the daily paying customer demand d_{tru} covers a typical range also used by other authors (cf. e.g. Atali et al. [2006]). A daily demand

[3]In contrast to de Kok et al. [2006] who include the value of RFID for preventing shrinkage due to theft, we only consider the value of the information that items were lost. On the one hand, high value items like apparel, media products, and consumer electronics are usually secured using electronic article surveillance (EAS) systems which have the same effect on theft prevention as item-level RFID.

Parameter	Values	Description
r_R	$\{20, 40^*, 60\}$	Unit sales price
m_R	$\{20\%, 30\%^*, 40\%\}$	Percentage retail markup
h_i	$\{15\%, 20\%^*, 25\%\}$	Percentage yearly holding cost
t	$\{0.05, 0.1^*, 0.15\}$	RFID tagging cost
d_{tru}	$\{2, 6^*, 10\}$	Mean daily paying consumer demand
γ	$\{1000, 5^*, 1\}$	Parameter of the distribution NB of the total daily demand d_{tot}
Q	$\{2d_{tru}, 6d_{tru}, 10d_{tru}\}$	Order quantity
L	$\{2, 6^*, 10\}$	Lead time of store replenishment orders in days
t_{aud}	$\{30, 60, 90\}$	Audit interval in days
α	$\{0\%, 1\%, ..., 5\%, \}$	Percentage daily loss of demand due to misplacement
β	$\{0\%, 1\%, ..., 5\%\}$	Percentage daily shrinkage
σ	$\{0, 0.1\sqrt{d_{tru}}, ..., 0.5\sqrt{d_{tru}}\}$	Standard deviation of transaction error
ϵ_1	$\{0, 1, ..., 5\}$	Shrinkage and transaction error combined (e.g. if $\epsilon_1 = 2$ then $\beta = 2\%$ and $\sigma = 0.2\sqrt{d_{tru}}$)
ϵ_2	$\{0, 1, ..., 5\}$	All sources of error combined (e.g. if $\epsilon_2 = 2$ then $\alpha = 2\%$, $\beta = 2\%$, and $\sigma = 0.2\sqrt{d_{tru}}$)

Table 3.1: Model parameters (* indicates default value)

of 2 is often associated with slow moving consumer goods, whereas a demand of 10 rather describes fast-moving consumer goods. The daily demand for a product depends on many factors not included in our model. However, since the product variety of high-impact products is higher (cf. Lee [2002]), their daily demand should be lower than the one of low-impact products.
The parameter range of γ which determines the variance of the total daily demand covers almost the entire range of variance that can be described using the Negative Binomial distribution. As noted earlier, a value of $1,000$ results in a variation of demand that comes close to the Poisson distribution. Setting $\gamma = 1$ results in the maximum variation the can be modeled using the Negative Binomial distribution.
The considered value range of the order quantity Q has been chosen in a way such that each order covers 2, 6, or 10 days of mean store demand respectively. In practice Q depends on the capacity of the shelves and back room, the efficiency and flexibility of the distribution center, and the transportation and fixed order cost.
The value range of the parameter L covers a relatively broad range of possible lead times. If the distribution center is in the direct neighborhood of the store, orders can be picked and shipped on short notice. The current trend

in logistics has lead to the centralization of warehousing capacity in order to realize economies of scale regarding operations. It is not unusual that a retail company that has stores all across Europe operates just one or two large distribution centers serving all these stores. Therefore a lead time in the region of one or two weeks is more realistic in practice.
The frequency of inventory audits partly depends on legal requirements and partly on individual practices of the retailer. A recent survey among 15 US based retailers carried out by Palmer and Richardson [2008] suggests that many retailers still conduct physical inventory audits one or two times in the fiscal year only. However, most of the companies contained in the sample also declared that they count the inventory at "high shrink" locations more often.
The parameter α serves as a model for the efficiency of the shelf replenishment process. Wong and McFarlane [2003] estimate the efficiency of the retail replenishment process from back room to shelf at 90-93%. Our model covers a range of 95-100%. Surveys by ECR Europe carried out by Roland Berger Strategy Consultants [2003] quote similar numbers. The chosen range of α seems conservative regarding these empirical observations. However, in a recent publication DeHoratius and Raman [2008] show that shelf availability can among other things by explained by product price, i.e. more valuable products are out of stock less frequently. The existent lack of shelf availability in high price settings should thus not be overestimated.
The parameter β describes the daily loss of stock due to shrinkage. We model a range of 0-5%. Reliable statistics about the actual degree of shrinkage in different retail settings is hard to obtain. Among other things this is due to the unwillingness of many retailer to publicly admit problems like theft and vendor fraud. However, quotes that can be found in retail blogs (e.g. Waters [2009]) and in recent industry publications (e.g. Alexander et al. [2002]) suggest that average shrinkage levels are as high as 2% of sales.
Transaction errors cannot be directly observed in practice and to the best of our knowledge there exist no documented estimates of the actual extent of the problem. Its existence and practical relevance, however, is undisputed (cf. e.g. Grimm [2004]). Grimm [2004] cites the results of a survey conducted among retailers that include a ranking of the "major obstacles to maintaining inventory integrity". According to the retailers top transaction errors are receiving errors, selling errors, and physical inventory counting errors. Interestingly, the study does not even consider shrinkage as a cause of inventory inaccuracy suggesting that transaction errors represent a practical challenge at least as important as shrinkage. In any case it can be assumed that the extent of inventory inaccuracy caused by transaction errors depends on the number of transactions involving the considered product (e.g. the number of

shipments received by the store over a certain period of time). In the absence of accountable information about the size of transaction errors in practice we have chosen to use similar parameter values for σ as Atali et al. [2006].

The simulation analysis proceeds in two steps. In the first step, the optimal reorder points of the store replenishment policy are computed using a simulation-based linear search technique. For each considered parameter configuration, the search procedure determines the value of the reorder point for which the average total cost, i.e. the sum of the average holding and lost sale cost, is minimal. During the determination of the reorder points for scenario S_{noRFID} the parameters α, β and σ were set to zero per cent respectively. This implies that the store manager does not take errors and inefficiencies into account when determining the store replenishment policy. In scenarios S_{info} and S_{RFID}, the error parameters to their respective values while calculating the reorder point. This allows for the computation of reorder points that minimize total cost if the corresponding inventory control policy is applied to the physical stock level.

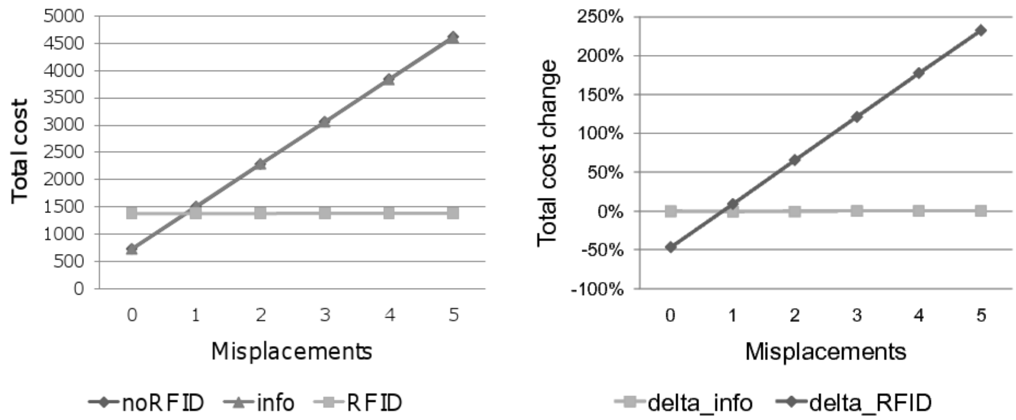
In a second step the optimal points determined in the first step are used to run the actual experiment. In scenario S_{noRFID} the corresponding store replenishment policies are applied to the virtual stock level I_{vir} which may deviate from the actual inventory level I_{phy}. Since in scenario S_{RFID} the virtual stock level never deviates from the actual one, the corresponding optimal replenishment policies are always applied only to the physical stock level.

The simulation starts at a the inventory state $I_{vir} = I_{phy} = Q$. Since we want to determine the long run average cost of the retail store, we let the simulation run for 360 simulated days before starting to record output values. By examining the development of stock levels we were able to validate that after this warmup period the inventory system has for sure reached a "swung in" state. The actual data collection took place in an interval of 1,080 simulated days, i.e. roughly three simulated years. Both for the computation of the policies as well as for the simulation experiments themselves, we repeated the simulation 1,000 times for each of the considered parameter configurations.

3.4.2 Results

In order to demonstrate the improvements resulting from the use of item-level RFID in the retail store we compare the results of the three considered scenarios, i.e. S_{noRFID}, S_{info} and S_{RFID}. For the initial comparison all parameters were set to their default values (indicated by * in Table 3.1) while the level of error was varied in order to reveal their effect on the total cost of the retail store.

Figure 3.1 shows the impact of the shelf replenishment error on the total cost of the store in the different scenarios. The total cost consists of the

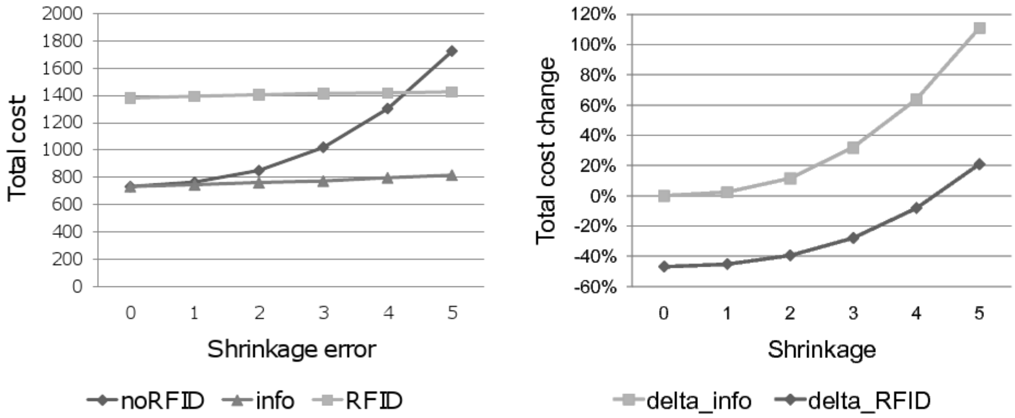


(a) (b)

Figure 3.1: Absolute (a) and relative change of the total cost (b) in the presence of misplacements (α)

accumulated holding, lost sale, and tagging cost. As one can see from the figure, the shelf replenishment error can lead to a significant increase of the total cost. In the default parameter configuration, the RFID solution becomes profitable below a shelf replenishment error of 1%. The informed policy provides no advantages in this case because we assume that misplacements cannot be defected without RFID.

Figure 3.2 shows the impact of shrinkage on the total cost of the store in the different scenarios. Unobserved shrinkage leads to a systematic departure of the virtual from the physical product stock level. If this inventory record inaccuracy is not considered in the determination of the reorder point (cf. in scenario S_{noRFID}), the efficiency of store replenishment decreases. Moreover, as one can see on the figure, the total cost in scenario S_{noRFID} increases exponentially. Figure 3.2 shows that using the optimal informed policy is an effective and less expensive means for fighting value loss resulting from the shrinkage error than item level RFID. If RFID is used to prevent stock inaccuracies, its use becomes profitable at shrinkage rates higher than



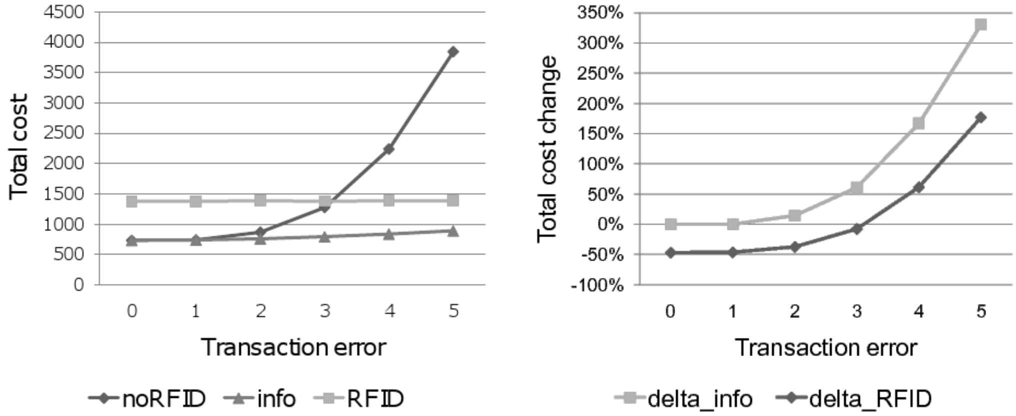
(a) (b)

Figure 3.2: Absolute total cost (a) and percentage cost savings (b) in the presence of shrinkage (β)

4% which should rarely occur in practice (cf. Waters [2009]).

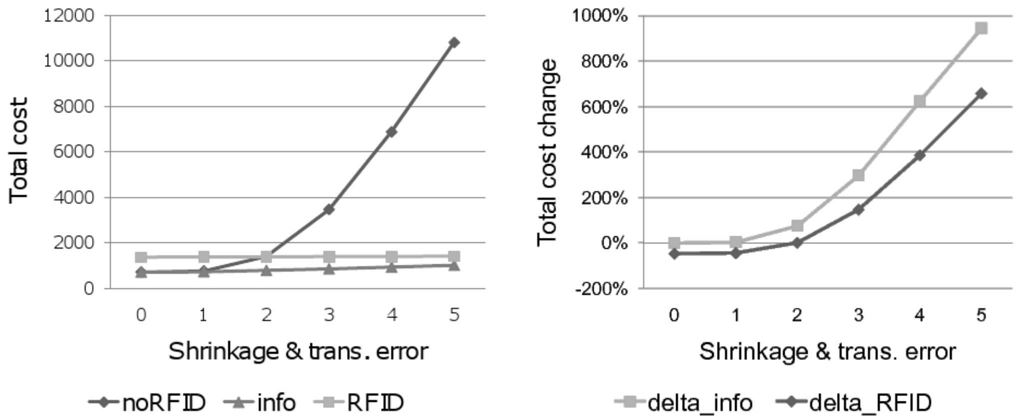
Figure 3.3 shows the impact of transaction errors on the total cost in the different scenarios. Transaction errors have a similar effect on the total cost of the retailer as shrinkage errors. Its negative effect on the total cost in scenario S_{noRFID} increases exponentially. At first glance this is surprising since transaction errors can lead to both a positive as well as negative departure of the virtual from the physical inventory level. However, since placing orders with the distribution center early or late is both sub optimal, the resulting inventory inaccuracy leads to a higher total cost. Again statistical information about the occurrence of transaction errors can help to adjust the reorder point in a way that the negative effect of inaccurate inventory levels on the total cost is significantly reduced. As one can see on Figure 3.3 (a), the total cost in scenario S_{info} is not entirely insensitive to the errors in the inventory data. In fact, its absolute cost advantage versus the use of item level RFID slowly decreases at higher levels of σ. However, for the considered range of the transaction error, the informed policy clearly beats the use of item-level RFID.

Figure 3.4 shows the combined impact of shrinkage and transaction errors on the total cost of the store in the different scenarios. As one can see from the figures, the combination of shrinkage and transaction errors has a similar impact on the retailer's cost as both errors alone. It leads to an exponentially increase of the total cost in scenario S_{noRFID}. A comparison of Figure 3.4



(a) (b)

Figure 3.3: Absolute total cost (a) and relative cost savings (b) in the presence of transaction errors (σ)

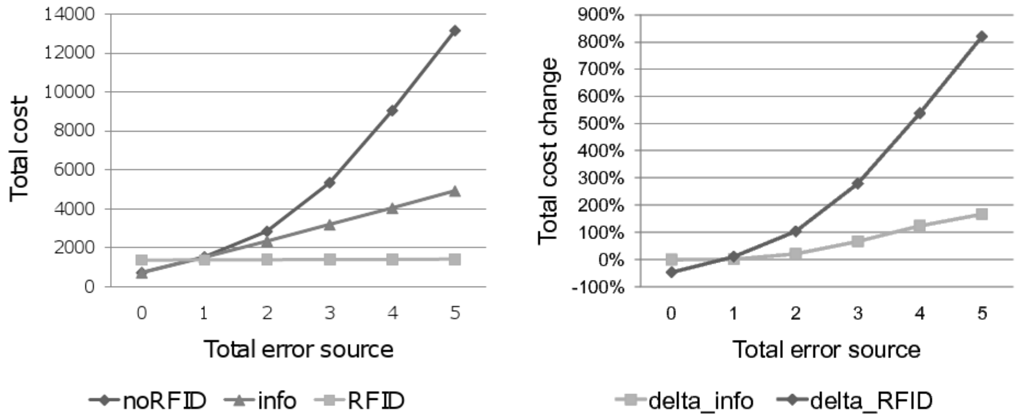


(a) (b)

Figure 3.4: Absolute total cost (a) and relative total cost saving (b) in the combined presence of shrinkage and transaction errors (ϵ_1)

with Figures 3.2 and 3.3 reveals that the negative effect of the two considered types of error "add up" in the sense that both errors taken together lead to higher costs than each type of error considered individually. For instance, at a level of $\beta = 2\%$ and $\sigma = 0.2\sqrt{d_{true}}$, the total cost in scenario S_{noRFID} is 851 Euros in the exclusive presence of shrinkage errors, 868 Euros in the exclusive presence of transaction errors, and $1,417$ Euros in combined presence of both types of error. As a consequence, the RFID break even level of ϵ_1 is lower than the corresponding level of β and σ. If the statistical distributions of shrinkage and transaction errors are known, the retailer can compute an optimal reorder point that is almost as effective as using item-level RFID but significantly cheaper within the considered range of ϵ_1 because we assume that the informed policy can be determined for free.

Figure 3.5 shows the combined impact of shelf replenishment, shrinkage, and transaction errors on the store profit in the different scenarios. The

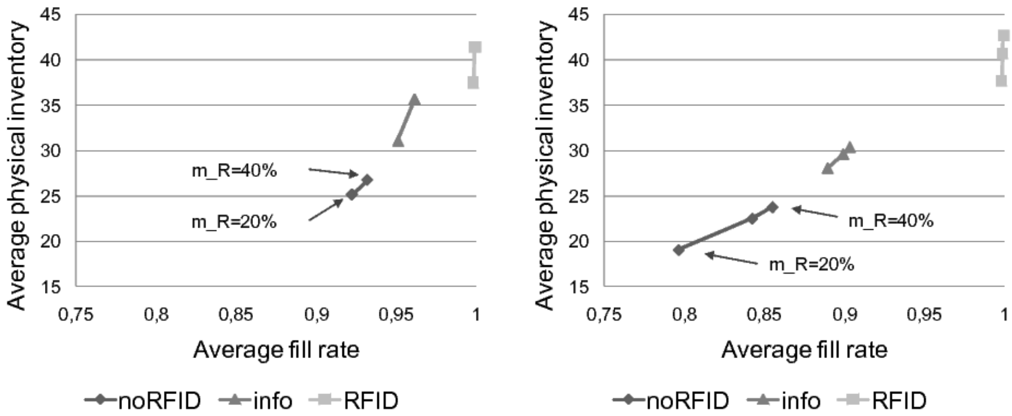


(a) (b)

Figure 3.5: Absolute (a) and relative change of the total cost (b) in the combined presence of shelf replenishment, shrinkage and transaction errors (ϵ_2)

simulation results reveal that not only the shrinkage and the transaction errors but all considered types of error add up. This is due the fact that misplacements and store replenishment practices are two separate processes. If both a particular product is neither available on the sales floor nor in the back room because, for instance, an orders with the distribution center has been placed too late, customer demand cannot be satisfied irrespective of the performance of the shelf replenishment process. On the other hand, if store replenishment works optimally but shelf replenishment does not, customer demand may in some cases not be satisfied although there is plenty of stock available in the back room. Using an informed store replenishment policy can be very effective for reducing the negative impact of inventory record inaccuracy. However, since it has no effect on the shelf replenishment process, the use of RFID is always more profitable from a certain level of the total error source onwards.

Figure 3.6 reveals how value is realized in the different scenarios. It shows the trade-off between the average stock level and the achieved fill rate for the levels 3 and 5 of the total errors source ϵ_2. It turns out that scenario S_{noRFID}



(a) (b)

Figure 3.6: Trade-off between average inventory level and fill rate for $\epsilon_2 = 3$ (a) and $\epsilon_2 = 5$ (b)

has both the lowest average inventory level and the lowest fill rate. The low average inventory level is due to the fact that in this scenario the store replenishment policy does not take the different error sources into account and therefore does not try to balance out their negative effect on the total cost by stocking more items. In scenario S_{info} the retailer uses accurate information about the different errors and adjusts the reorder point in order to reduce the negative impact of the errors on the total cost as much as possible. Figure 3.6 shows that this allows her to satisfy more demand but also forces her to carry more inventory on average. If RFID is used to observe the movement of product stock in the shop, the fill rate increases to almost 100%. The optimal fill rate in scenario S_{RFID} is very high because the penalty for stock outs is high compared to the penalty of stocking too many items. For the default parameter configuration, each lost sale due to stock out results in an immediate loss of 12 Euros (40 Euros $\times$ 30%) whereas keeping an item in the

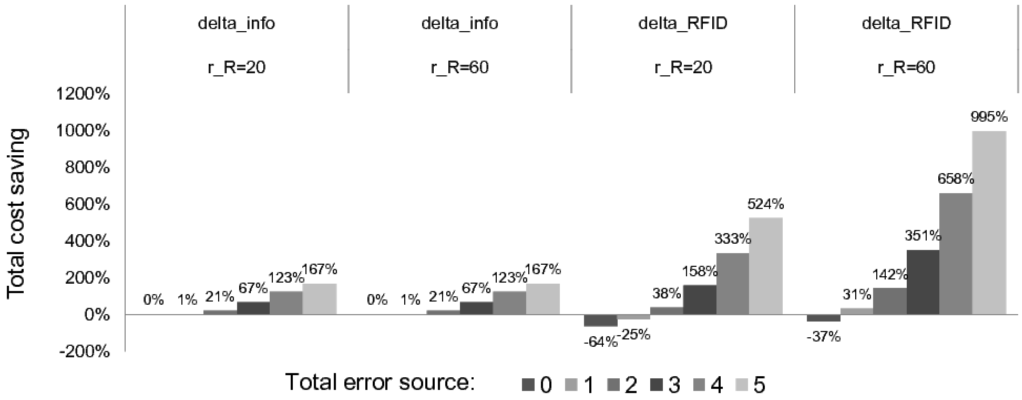


Figure 3.7: Sensitivity of the percentage profit changes with respect to the retail price r_R

inventory for one year costs only 2.4 Euros (40 Euros $\times$ 30% $\times$ 20%). The comparison of the Figures 3.6 (a) and (b) reveals that at higher levels of the total error source, the observed effects are more significant. In particular, the gaps between the fill rates achieved in the respective scenarios widen and the differences between the average stock levels also become greater.

3.4.3 Sensitivity Analysis

To make sure that the obtained simulation results are sufficiently robust within the considered value ranges of the model parameters, we conducted a sensitivity analysis. A sensitivity analysis also provides insights regarding the type of retail environment that benefits most from item-level RFID. In the course of this analysis we observed the changes of the percentage cost savings achieved by the informed and the RFID system in response to the unilateral variation of the value of each parameter listed in Table 3.1 within its considered range. For the sake of brevity, we only consider the total errors source ϵ_2.

Figure 3.7 shows the impact of changes of the retail price r_R on the percentage total cost saving when moving from scenario S_{noRFID} to scenarios S_{info} or S_{RFID}. The value of the informed policy is not affected by different product prices. This is due to the fact that an increase of r_R leads to a relative increase of both the penalty and the holding cost which is accounted for in the computation of the reorder point. In contrast to that, the percentage cost saving resulting from the use of RFID increases with higher values of r_R. This result can be explained in the following way. Increasing r_R from 40 to 60, i.e. by 50%, results in a percentage increase of the unit lost sale

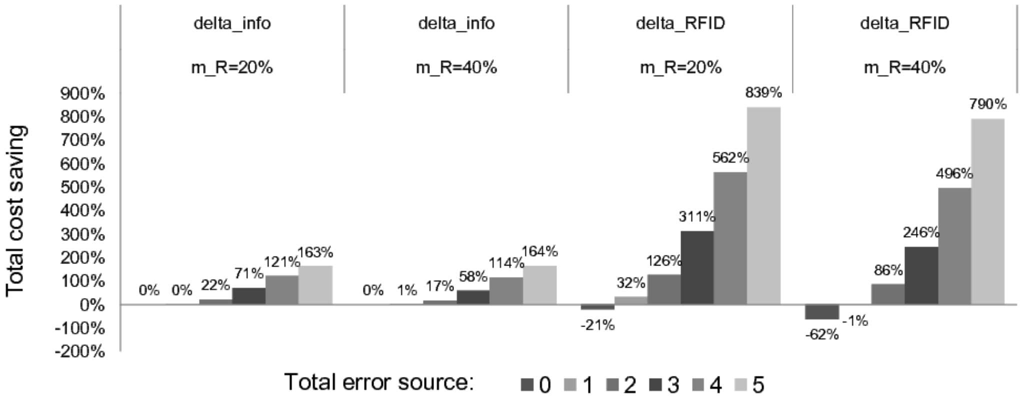


Figure 3.8: Sensitivity of the percentage total cost savings with respect to the product's percentage retail markup m_R

cost and the holding cost by the same percentage. Since the informed policy entirely relies on additional inventory to compensate the negative impact of inventory inaccuracy, the change of r_R does not have any effect on the relative advantage of S_{info} over S_{noRFID}. Figure 3.6) shows that by using RFID the highest possible fill rate can be achieved while carrying less stock than in scenario S_{info}. In contrast to additional safety stock, the cost of RFID tagging is independent of r_R. This explains the increasing value of RFID at higher product prices: On the one hand more lost sales can be prevented while on the other hand it costs relatively less to do so as r_R increases.

Figure 3.8 shows the impact of changes made to the percentage retail markup m_R of the considered product on the percentage total cost saving in the scenarios S_{info} and S_{RFID}. The figure reveals that the markup m_R has a significant but small influence on both the value of the informed policy and item level RFID. For the considered parameter values, a smaller retail markup leads to a slightly lower advantage of both scenarios compared to the benchmark scenario S_{noRFID}. The explanation for this result can again be found by analyzing the trade-off between average inventory and fill rate. A lower value of m_R results in a lower average stock level because carrying more inventory becomes more expensive for the store. At $m_R = 20\%$ the responsiveness of the store in scenario S_{noRFID} is significantly lower than at $m_R = 40\%$. In a situation where the responsiveness of a distribution system is already low, inventory inaccuracy leads to even higher stock-out rates. Therefore the advantages resulting from using an informed policy or item level RFID is also higher at lower values of m_R.

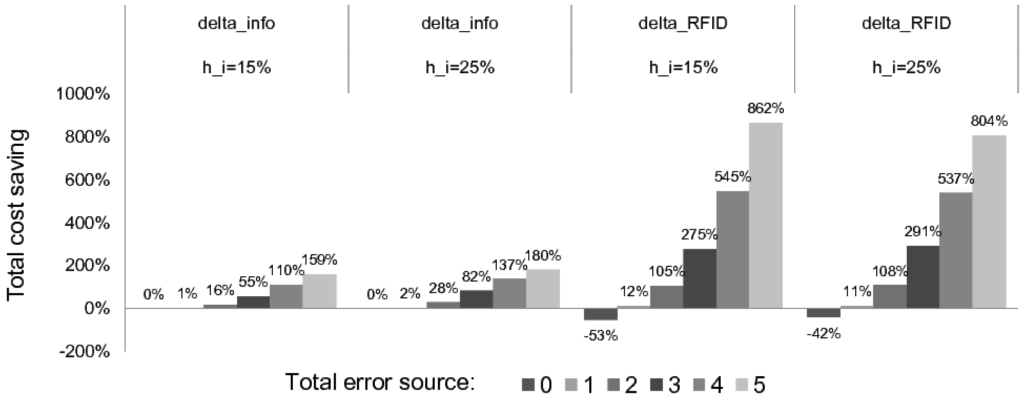


Figure 3.9: Sensitivity of the percentage total cost savings with respect to the product's percentage yearly holding cost factor h_i

Figure 3.9 shows the impact of changes made to the percentage yearly holding cost factor h_i on the percentage total cost savings realized in the scenarios S_{info} and S_{RFID}. The figure reveals that a higher percentage holding cost leads to a slightly higher value of the informed policy. On the one hand, the responsiveness of the store in scenario S_{noRFID} is lower since the retailer carries less safety stock. This increases the loss of value due to stock out and increases the value of the informed policy. On the other hand, a increase of h_i also leads to a decrease of the efficiency of the informed policy because it depends on a higher level of safety stock. The positive effect has gained the upper hand in this case. The impact of h_i on the percentage cost saving resulting from RFID usage is unclear. At higher values of ϵ_2 it has a slightly negative effect whereas on lower levels of ϵ_2 the effect is rather positive. Higher values of h_i lead to higher total costs both in scenario S_{noRFID} and S_{RFID}. In the former it reduces the "optimal" amount of safety stock and thereby lowers the fill rate, in the latter it increases the cost of stocking more items to prevent stock outs resulting from replenishment errors. Since these effects play against each other, the overall impact of h_i within the considered value range is limited.

Figure 3.10 shows the impact of changes made to the unit RFID tagging cost t on the percentage total cost saving in the scenarios S_{info} and S_{RFID}. The impact of the unit RFID tagging cost on the respective cost savings is straightforward. Since RFID is not used in scenario S_{info}, t has no effect on the corresponding cost savings. In contrast to that, the cost saving realized in scenario S_{RFID} is highly dependent on the on the tagging cost. The higher the tagging cost, the lower the corresponding cost saving. However, as Figure

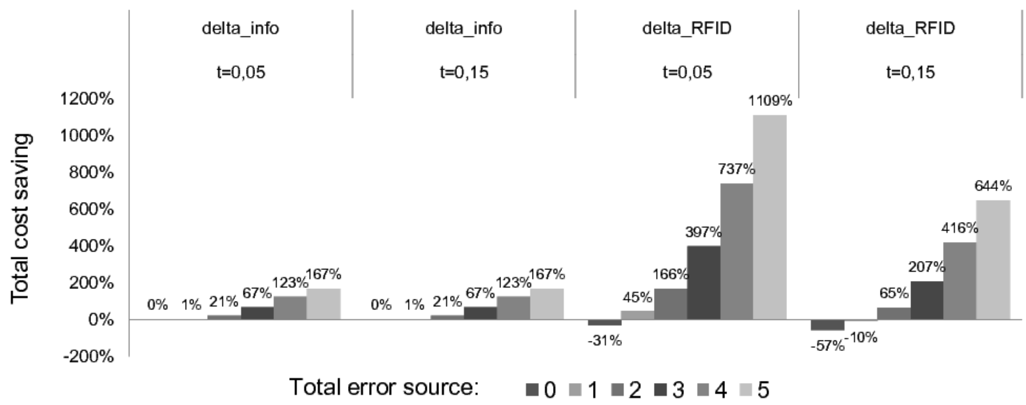


Figure 3.10: Sensitivity of the percentage total cost savings with respect to the unit tagging cost t

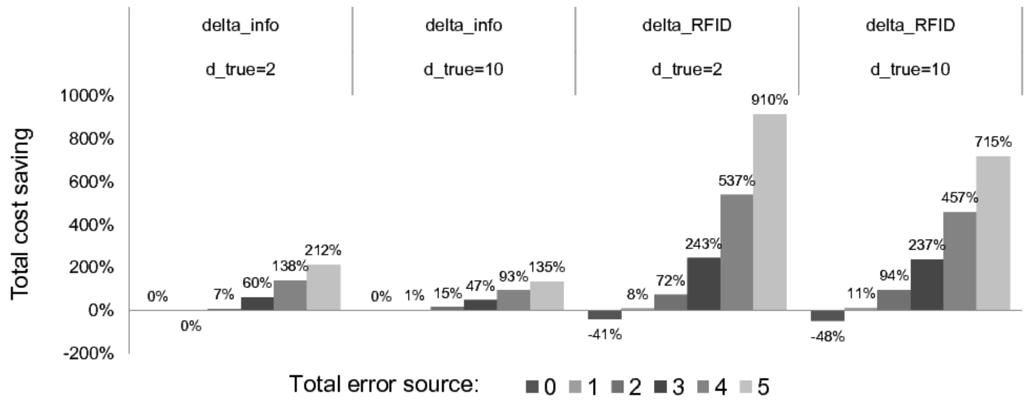


Figure 3.11: Sensitivity of the percentage total cost savings with respect to the daily paying customer demand d_{tru}

3.10 shows, even at a relatively high tagging cost of 15 Eurocents the value of ϵ_2 that makes the use of RFID profitable lies close to 1.

Figure 3.11 shows the impact of changes made to the daily paying customer demand d_{tru} on the percentage total cost saving when moving from scenario S_{noRFID} to scenarios S_{info} or S_{RFID}. The impact of d_{tru} on both the cost savings achieved by the informed policy and the value of RFID depends on the error level. At lower values of ϵ_2 it is slightly positive, at higher values it becomes negative. We have not found a straightforward explanation for this effect.

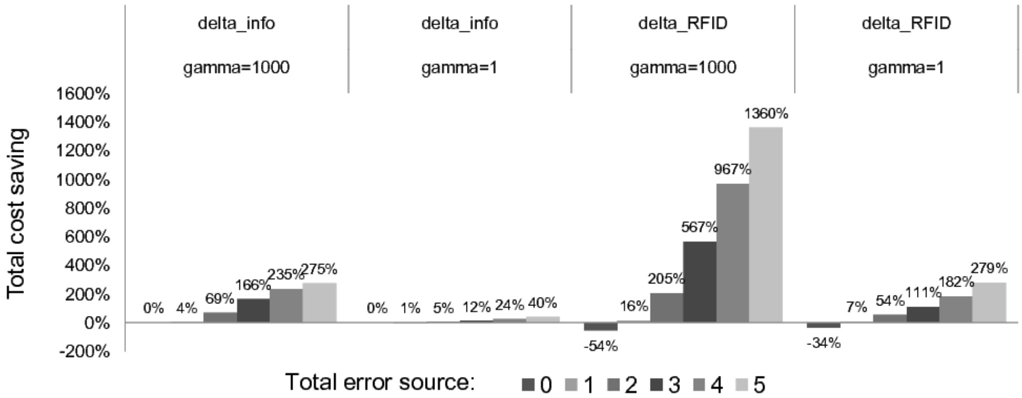


Figure 3.12: Sensitivity of the percentage total cost savings with respect to the demand variance expressed by the parameter γ

Figure 3.12 shows the impact of the parameter γ on the percentage total cost saving when moving from scenario S_{noRFID} to scenarios S_{info} or S_{RFID}. Both the relative advantage of scenario S_{info} and scenario S_{RFID} over scenario S_{noRFID} is higher if the variance of demand is lower. This observation can be explained by the fact that the error sources introduce additional uncertainty into the model and that the resulting higher variability of the demand and the inventory levels is not accounted for by the order policy in scenario S_{noRFID}. If γ is smaller (i.e. if regular variance of demand is higher), the degree of uncertainty caused by the total error source relative to the degree of uncertainty caused by the regular demand uncertainty becomes smaller. Thus, the negative impact of the error source and therefore the profit improvements achieved by the informed policy or RFID are significantly lower at lower values of γ.

Figure 3.13 shows the impact of changes made to the order quantity Q on the percentage total cost saving when moving from scenario S_{noRFID} to scenarios S_{info} or S_{RFID}. Smaller order sizes generally increase the efficiency of inventory systems (cf. Chopra and Meindl [2004]). Since shipments from the distribution center arrive at the store in shorter time intervals, the order policy in the status quo is configured to provision less safety stock on average. On the one hand the reduction of safety stock allows for realizing cost savings. On the other hand it makes the system more vulnerable to unexpected demand variability or execution errors. Therefore the negative impact of the total error source is severe in relative terms if the order size is smaller. This in turn reduces the relative value of both the informed policy and RFID usage.

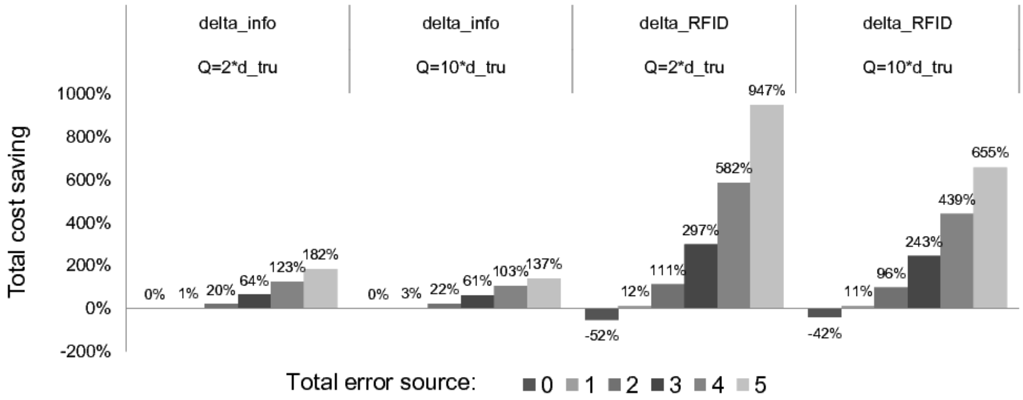


Figure 3.13: Sensitivity of the percentage total cost savings with respect to the order quantity Q

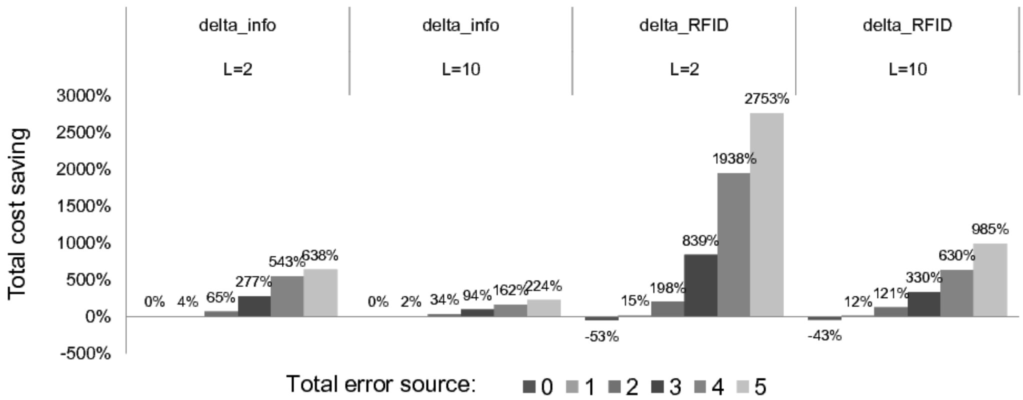


Figure 3.14: Sensitivity of the percentage total cost savings with respect to the order lead time L

Figure 3.14 shows the impact of the order lead time L on the percentage total cost saving when moving from scenario S_{noRFID} to scenarios S_{info} or S_{RFID}. As the figure demonstrates, the increase of L from 2 days to 10 days significantly reduces the value of the informed policy and RFID. Lower lead times can make inventory systems far more responsive since lead times represent the time that a continuously replenished store needs to react to demand changes. If lead times are longer, more safety stock needs to be maintained in order to satisfy demand in the optimal way. If they are shorter, the level of safety stock can be reduced without decreasing the average fill rate. In scenario S_{noRFID} the error sources are not taken into account which has a significantly negative effect on the performance of the retail store because it

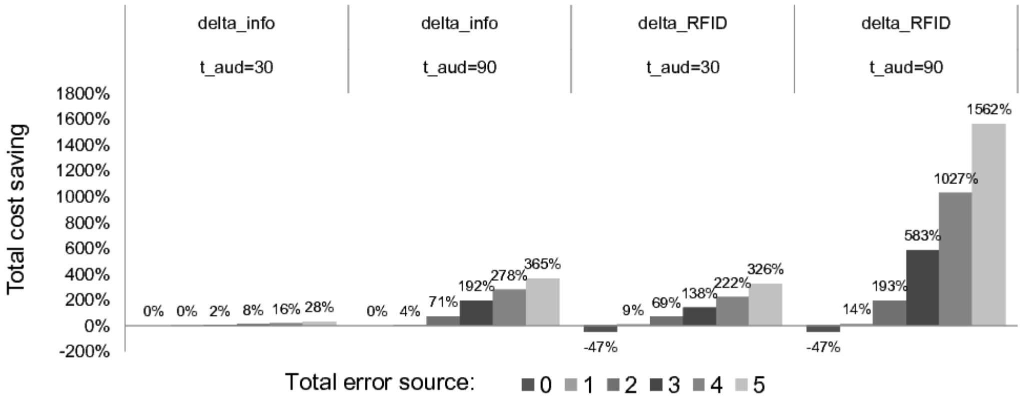


Figure 3.15: Sensitivity of the percentage total cost savings with respect to the time period in between two inventory counts

increases the number and duration of stock-out situations. If the safety stock is higher, this negative effect is dampened to a certain degree. Thus, since the "optimal" safety stock decreases with smaller values of L, the value of being able to adjust the reorder point based on information about the error sources and the value of full visibility achieved by item level RFID is higher at smaller lead times.

Figure 3.15 shows the impact of changes made to variance of the total daily demand d_{tot} for the product on the percentage total cost saving when moving from scenario S_{noRFID} to scenarios S_{info} or S_{RFID}. The impact of the duration between two successive physical inventory counts, like the impact of the tagging cost, is straightforward. If it is longer, the inventory error becomes greater because it can accumulate for a longer time. Thus, the less frequent inventory audits are conducted, the less efficient is the store replenishment process.

Summarizing the results of the sensitivity analysis we can say that switching from scenario S_{noRFID} to scenario S_{info} or S_{RFID} can always be worthwhile irrespective of the considered store characteristics. However, the different model parameters reflecting the characteristics of the supply chain can have a significant influence on the extent of the relative cost savings realized by implementing an informed policy or RFID. They are significantly higher for higher values of the sales price r_R and the length of the audit period t_{aud}, and significantly lower for higher variances of demand (expressed by the parameter γ), the order quantity Q, and the order lead time L. Compared to the already mentioned model parameters, the percentage retail markup m_R, the percentage yearly holding cost h_i, and the mean daily paying customer demand d_{tru} have a rather limited and sometimes mixed impact on the relative cost changes. Irrespective of the choice of input parameters, the break even total error source ϵ_2 lies close to 1, i.e. in a very conservative range considering the current state of knowledge about the extent of the different error sources (cf. the figures cited in Section 3.2).

3.5 Limitations

Our work is subject to several limitations which are addressed in this section.

Firstly, quantifying the information value of RFID and comparing it with the variable RFID cost is not sufficient to make a sound investment decision. On the one hand, the fixed cost of deploying and operating an item-level RFID infrastructure in a shop can be significant and are not considered in this work. However, these costs can be estimated fairly well in practice and do not depend on the other model parameters (unlike the considered tagging cost). Furthermore, the implemented RFID infrastructure used not only for one type of product, but for all tagged products being sold in the store. Thus, the ultimate return on investment resulting from the usage of item-level RFID can be calculated by taking the cost savings resulting from our model and comparing them to the estimated fixed costs.
On the other hand, a number of possible benefits of item-level RFID in stores were not considered here, in particular we do not explicitly consider time and labor cost savings resulting from the use of RFID. Item-level RFID can for instance save time (and the corresponding labor cost) at the goods receipt, during inventory audits, or at the check-out. However, provided the subset of products we focus on (e.g. apparel, consumer electronics, books, etc.), those time savings should be rather small because the product volumes sold by the corresponding stores are lower. For instance, time savings at the store check-out depend on the number of products scanned per customer, which can be expected to be very low for high-impact products. Some authors also assume that item-level RFID can help to prevent shrinkage in the retail store (cf. e.g. de Kok et al. [2006]). However, provided that the type of product we consider in this dissertation are usually already secured using established retail security systems, it is unlikely that RFID will lead to a significant drop of shrinkage levels.

Secondly, we assume that the retailer incurs a lost sale whenever the consumer does not find the product on the shelves. This is a very strong assumption since in practice not every stock out situation results in a lost sale for the company. A number of recent studies on shelf availability (e.g. Gruen et al. [2002], Roland Berger Strategy Consultants [2003], Grocery Manufacturers of America/A.T.Kearney/IBM [2007]) provide some insight into how consumers react to stock outs. On average only 40% are completely lost. In the remaining 60% of the cases consumers either delay the purchase or substitute the product they actually wanted to have against another one that is available on the shelves. Unfortunately, all mentioned studies are on typical low-impact products such as grocery, detergents, etc. Therefore the figures cannot be used to back our assumptions. However, one can argue that high-impact products have a higher lost sales fraction because they are more expensive than low-impact products and have less substitutes in the same store.

Thirdly, we assume that the accurate and timely data on the location of products in the store completely prevents phantom stock-outs. This assumption implies that there exist sufficient human resources to keep product availability at the maximum level and that the RFID shelf replenishment policy does not cause higher labor cost than the non-RFID policy. Other researchers have taken the trade-off between higher execution cost and the value of visibility explicitly into account (cf. e.g. Thiesse and Fleisch [2007]).

Fourthly, an important assumption we make is that the RFID system is 100% reliable, i.e. that RFID allows for tracking the location of every tagged product in the back room and on the shelves at any time. Of course this assumption may not be true under all circumstances. However, recent item-level RFID pilots suggest that low read rates do not represent a significant problem any more. In particular, recent progress in the domain of reader protocols and transponder design has mitigated many initial problems regarding the use of the technology in retail settings.

3.6 Conclusions

In this chapter we have analyzed the impact of different error sources on the performance of the inventory control in a typical retail store that uses a reorder point type of inventory policy. The considered types of error are misplacements, shrinkage, and transaction errors. By assuming that the use of item-level RFID leads to the elimination of inventory inaccuracy due to shrinkage and transaction errors and reduces lost sales due to phantom stock-outs to zero, we are able to estimate its financial value. The existence of the

considered types of errors is undisputed in practice and has also been proven by recent scientific research. More difficult to estimate is their actual extent in different retail settings. Moreover, their financial impact depends on many different environmental variables which can both affect the extent of the errors themselves or moderate their financial impact. We did not conduct an empirical analysis of the extent of the considered errors. Instead, we justified the values of our model input parameters on previous work. Therefore we were only able to analyze the effects of environmental variables on the causal link between errors and financial impact, not the factors abetting inventory inaccuracy or misplacements. However, by analyzing the effect of different error levels and combinations of the error sources, we provide a broad information basis that can be used as cost approximations once estimates of the different error levels are known.
Our results show that there exists an adjusted policy that almost eliminates the negative effect of inventory inaccuracy resulting from shrinkage and transaction errors. The question is whether the information necessary for computing the adjusted reorder points is available. A type of information that is usually available is the departure of the actual from the system inventory level of all products that was determined during the physical inventory audits. However, this information is not sufficient to provide reliable statistical estimates of the underlying errors sources. In particular the variance of shrinkage and transaction errors is hard to predict based on this data. Computing the adjusted reorder point based on wrong estimates of the statistical properties of the errors sources may significantly reduce the profitability of the informed policy versus the use of item-level RFID.

Last but not least, the use of item-level RFID for unique product identification has repeatedly triggered debates about the infringement of consumer privacy. The problem is not so much that the retail company finds out which products a particular person buys. Wal-Mart has done so for several years without using item-level RFID (cf. Hays [2004]). What seems to bother people most is the fear that RFID tags will remain attached to the product after it has been sold and thus allow for tracking people in their every day lives. In fact, this scenario is not as unlikely as it may seem at first glance. Although most retail companies will not be interested to track people outside their stores, third parties may very well be interested. In fact, it is technically feasible to track people based on the tagged objects that they carry around (e.g. their clothes, shoes, bags, iPods, etc.). What is needed is a suitable RFID reader device and a database that allows for putting the identifier stored on the tag into an informative context. Against this background it has to be noted that passive RFID tags can be deactivated at the store check out which disables further use after the sale (cf. Spiekermann and Evdokimov [2009]). The effectiveness of this measure can be accurately monitored. Furthermore, there already exist so-called privacy enhancing technologies (PETs) that enable the consumer to use RFID tags after sale only if it is beneficial for them and deactivate them otherwise (cf. Spiekermann and Evdokimov [2009]). Thus, similar with the integration of RFID technology into official passports, it is rather a matter of regulation whether personal privacy is preserved or lost.

Using a numerical simulation we have shown that item-level RFID tagging of typical high-impact products is profitable even under conservative assumptions regarding the extent of typical execution errors in retail operations and if the tagging cost is borne by the retailer alone. This observation corresponds with recent practical experience in selected retail settings, in particular apparel stores (cf. e.g. Gaudin [2008], Kurt Salomon Associates [2005], Goebel et al. [2009c]). If item-level tagging becomes common practice – even if it is only one industries such as apparel – the resulting demand for standardized RFID hardware (especially passive RFID transponders) may already lead to a significant drop of the RFID usage cost which will result in further RFID adoption.

Chapter 4

The Value of Item-Level Transshipments and RFID

4.1 Introduction

Supply chain management practices play an increasingly important role in gaining a competitive edge. Leading companies from different industries such as Dell, Wal-Mart, and Zara are successful in the marketplace not only because they offer products that consumers want to buy but also because their logistic processes are aligned to efficiently delivering these products at the right time and quantity. Dell has optimized the trade-off between product configurability and speed of delivery (cf. Chou et al. [2004]). Wal-Mart is able to offer very low prices among other things due to highly efficient logistics operations (cf. Schrage [2002]). Zara successfully applies a quick response formula consisting of lead time reduction and efficient information sharing mechanisms (cf. Ferdows et al. [2004]). When taking a closer look at these market leading companies it turns out that nowadays information technology plays a vital role in the successful implementation of supply chain strategies. Dell has closely linked the control of its supply chain practices, which support high product configurability, to its website (cf. Chou et al. [2004]). On the one hand, this allows customers to configure and order the computer they want. On the other hand, the web site can be used as a means to collect information on consumer preferences and quickly adapting the available choice of configurations to changing consumer requirements. Wal-Mart has invested heavily in information technology in order to automate processes and collect relevant sales data (cf. Schrage [2002]). Their investment into high process automation pays off due to the high product volume sold by Wal-Mart stores around the world every day. Apart from using IT to automate processes, they also leverage the information that can be extracted from the data collected at the check out. In particular, Wal-Mart's managers are able to predict demand more accurately than many other companies due to their ability to identify useful patterns in the huge amounts of sales data stored in their data warehouse (Hays [2004]). Zara takes advantage of technology that facilitates the flow of information reflecting consumer trends or technologies which help to reduce the lead time such as computer aided design and fully automated distribution centers (Ferdows et al. [2004]). In contrast to Wal-Mart Zara's managerial focus lies on the reaction to consumer demand rather than its prediction and efficient satisfaction.

The most fundamental trade-off in supply chain management exists between efficiency and responsiveness (Chopra and Meindl [2004]). Efficiency in the supply chain context refers to the minimization of production and distribution cost; responsiveness refers to the degree to which a supply chain is able to efficiently cope with demand uncertainty (Lee [2002]). The trade-off exists because responsiveness has to be paid for, e.g. in the form of higher safety inventory or the acceleration of transportation. As the examples mentioned previously show, the use of information technology can have consequences regarding both the efficiency and responsiveness of supply chains. For instance, if it enables the reduction of labor cost in a distribution center it has an impact on efficiency. If it enables or improves supply chain practices that reduce the exposure to demand risks it has an impact on responsiveness. In this chapter we address performance improvements resulting from improved responsiveness that can be achieved by using item level transshipments between retail stores. Item-level transshipments represent an innovative supply chain practice that can help to improve the performance of retail supply chains. A crucial precondition for their use is effective decision support and efficient processes. Currently, most retailers shy away from implementing transshipments since they do not trust their inventory data and because they fear the handling cost to exceed the benefits.
Radio frequency identification (RFID) is an information technology whose impact on supply chain management is steadily increasing. Whereas RFID based case and pallet level tracking has become relatively common, the tagging of individual items has not exceeded the pilot testing at many companies. Item level RFID could enable new retail processes because it allows for the accurate and timely localization of inventory. It therefore promises to increase both the handling efficiency and control of supply chain processes wherever products are handled individually. Item level transshipments require a very high degree of individual product handling. Furthermore, it is immediately apparent that they only make economic sense for rather high value products

whose margins justify the costly reallocation of products to stores during the sales season. Transshipments therefore represent an innovative supply chain practice that could be enabled by RFID tagging and tracking consumer goods with high-impact characteristics (cf. Chapter 1). Apart from providing the basic automation and information benefits investigated in Chapters 2 and 3 of this dissertation, they could lead to the realization of additional transformation benefits Tellkamp [2006].

In the following section we provide an overview of the related literature on distribution system responsiveness, transshipments, and RFID applications in retail distribution systems. Thereafter we describe the model we use to measure the performance impact of transshipments. Finally we summarize the results and insights gained from an exemplary simulation study.

4.2 Related Work

4.2.1 Distribution System Responsiveness

Fisher [1997] describes how using the "right" supply chain practices can lead to significant performance improvement. In particular, he outlines the potential of "aggressively" reducing lead times in markets that are subject to high demand uncertainly. Other approaches to reduce a supply chain's exposure to the demand risk include the efficient pooling of stock (cf. Chopra and Meindl [2004]) and effective information sharing practices (cf. Lau et al. [2004]). Transshipments represent another management lever to improve the responsiveness of goods distribution. The term transshipment refers to the practice of shipping stock from one outlet with excess stock to another one that faces stock-outs. As previous research has shown, the implementation of transshipment processes can significantly improve the performance of a distribution system.

4.2.2 Transshipments

A recent survey by Chiou [2008] provides a comprehensive overview of the current state of research on transshipments. Numerous articles have investigated the value of transshipments in service part distribution systems (cf. e.g. Lee [1987]). Since the demand for service parts (e.g. machine components) is usually low and highly uncertain and because of the high value of such parts, transshipment policies can often increase the efficiency of such systems. Recently, transshipments have also been considered as a measure to improve the responsiveness of supply chains for consumer products. Due to the relatively high cost of handling and transporting single products, their use is especially promising for rather high-priced products such as apparel, consumer electronics, and toys. According to Chiou [2008], transshipment policies can be of the emergency and preventive type. The applicability of either type of policy depends on the whether customer demand is backlogged or not, i.e. if the customer is willing to wait for the product or not. Emergency lateral transshipments are only useful if customers are willing to wait at least for a short time, whereas preventive transshipments are supposed to balance the inventory at several retail outlets in order to prevent out of stock situations. The customers' willingness to wait will be higher if the product they are looking for is more unique and thus harder to substitute which is a typical property of high-impact products.

The determination of the optimal timing and quantities of transshipments has turned out to be highly complex. Optimal policies with limited generalizability have been proposed among others by Robinson [1990], Rudi et al. [2001], Jönsson and Silver [1987], and Bertrand and Bookbinder [1998]. Whereas the work of Robinson [1990] and Rudi et al. [2001] is on emergency transshipments, Jönsson and Silver [1987] and Bertrand and Bookbinder [1998] consider preventive transshipments. Interestingly, none of these authors have explicitly investigated the lost sales case which is a requirement to apply transshipment policies to retail settings. Some authors have analyzed transshipment policies using numerical optimization models and simulation (e.g. Herer et al. [2006]). Their optimization procedures are sufficiently comprehensive to take the complex trade off between inventory holding, stock out and transportation costs into account. The work of Banerjee et al. [2003] compares two different types of preventive transshipment policies: (i) ad-hoc transshipments for preventing pending shortages and a (ii) transshipment policy based on system-wide inventory balancing which is performed once per review cycle. They come to the conclusion that the first policy type is more effective in preventing stock-out incidents. Other authors have specified and evaluated the performance of less sophisticated transshipment mechanisms that do not implicitly optimize all relevant cost tradeoffs (e.g. Lee et al. [2007]).

The implementation of transshipment operations naturally requires a high degree of inventory visibility across the entire distribution system. Since the product quantities that need to be transshipped at any given time are computed based on the respective inventory levels at the different locations, the accuracy of this data can have a substantial effect on the quality of allocations and in turn on the efficiency of transshipment operations (cf. Goebel and Günther [2009]).

4.2.3 Value of RFID in Retail Distribution

As we mentioned in the introductory chapter of this dissertation, there exist three general types of RFID benefits in supply chain management:

1. Labor and time saving due to process acceleration (referred to as the value of automation).

2. Benefits from higher visibility and data quality (referred to as the value of information).

3. Benefits resulting from newly introduced business practice enabled by RFID (referred to as the value of transformation).

Labor and time savings can only be determined based on a detailed analysis of the existing processes that involve the handling of products. Item-level RFID can save process cost in process steps that involve item-level counting of products. Case studies investigating the value of item level RFID usually consider the time savings it enables at the goods receipt, during regular inventory audits, and at the check out (cf. Kurt Salomon Associates [2005]).
A number of authors have investigated the potential of RFID for increasing the accuracy and accessibility of inventory information and thereby indirectly improving the efficiency of supply chain management practices (cf. Lee and Özer [2007]). Inventory inaccuracy can come into existence for different reasons that can be subsumed under the terms shrinkage and transaction errors (cf. Raman et al. [2003], DeHoratius and Raman [2008]). The effect of inventory inaccuracy on the performance of typical inventory order policies was analyzed by several authors (e.g. Rekik et al. [2008], Atali et al. [2006], Thiesse and Fleisch [2007]). Atali et al. [2006] for instance quantified its impact on the performance of retail inventory management. The only work we are aware of that investigates the effect of inventory errors on the performance of a whole supply chain is of Fleisch and Tellkamp [2004] who simulated the working of a typical retail supply chain.
To the best of our knowledge, the use of item-level RFID has not been considered as a means to *enable* the lateral transshipment of consumer products. According to the RFID benefit categorization repeatedly cited in this dissertation this type of RFID benefit belongs to the transformation value category because lateral transshipments of product stock between retail outlets are an innovate supply chain practice that can be enabled by item-level RFID. In order to provide value to a retail company, transshipments must be effectively planned and executed. Due to its unique properties RFID can help with both. On the one hand, it can increase the accuracy of information about the location and state of individual products in the store network. On the

other hand, it can provide the required data to store front ends that increase the efficiency of item-level transshipment processes. These processes include (i) the picking of transshipment batches from the sales floor and back room of the source stores, (ii) the transportation of the transshipment batches from the source to the destination stores, and (iii) the receipt and put away of transshipped products at the destination stores. In process step (i) accurate RFID data showing the exact location of products can help to generate optimal routes for the assembly of transshipment orders. The picking process can also be monitored and supported in real time, e.g. by dedicated applications running on personal digital assistants (PDAs) used by the store personnel. The PDAs can be linked to the store's inventory management system which in turn has access to real-time RFID data. The trolley used for collecting products can be equipped with an RFID reader that automatically updates the picking list and interacts with the PDA giving directives to the employee. In process step (ii) the efficiency of the shipment operations can be supported by RFID. Using the most efficient way to conduct transshipments implies the consolidation of several transshipment orders whenever this is possible. Whereas the required optimization of the transshipment routes does not require RFID, the execution of the optimal plan may benefit from its use both in terms of speed and accuracy. Contactless data collection via RFID readers used during the loading and unloading activities can streamline the necessary verification and documentation processes.

In process step (iii) the store personnel does not need to manually count incoming transshipments and update the inventory levels. Furthermore, the efficiency of the put away process can be maximized using the same set of technologies described in step (i). Based on accurate information about the amount of products that are currently available on the sales floor and in the back room a routing algorithm can be used to minimize the time required to put the transshipped products at the right place.

In the following we use an economic model of a typical retail store network to demonstrate the value of item-level transshipments.

4.3 The Model

Our supply chain model comprises one distribution center and n retail outlets that belong to the same company. The type of product under consideration is of the "flow through" type, i.e. it is only buffered for a short time at the company's distribution center(s). The product is sold for r_R Euros in the outlets. The per unit sourcing cost of the product is $c_R = (1 - m_R)r_R$ where m_R represents the retail markup. We assume that if products are tagged on the item-level, the unit tagging cost t adds up to the product's wholesale price without having an effect on the markup. At the distribution center the shipments received from the suppliers of the retail company are split up into smaller batches destined for the different retail outlets. The sales period of the product is Δ_{sales} days. We make the assumption that after this time the product can only be salvaged obtaining s Euros per unit. The variable s can be computed according to Equation 4.1.

$$s = h(1 - m_R)r_R \tag{4.1}$$

We furthermore assume that the sales period of the considered product is synchronized across the retail outlets, i.e. all n retail outlets receive their respective share of the product at the same day and remove it from the regular shelves S days later. This is a realistic assumption for many products with high-impact characteristics because the marketing effort accompanying the distribution of products usually comprises several stores run by the same company.

We assume that in the status quo the demand for the considered product needs to be satisfied immediately from the on-hand stock available at the outlets, i.e. customers walk away if they do not find the product they are looking for. Each lost sale thus results in a penalty of $m_R r_R$ for the company. The lost sale assumption can be justified by our focus on high-impact products. The chances that consumers immediately buy a substitute available at the store is rather small for this type of products because they tend to be more unique.[1].

We assume that the daily demand for the considered product follows a Negative Binomial distribution $NB(\gamma, p)$. If the mean daily demand is μ_d, the parameter p can be computed using the following Equation.

$$p = \gamma/(\mu_d + \gamma) \tag{4.2}$$

According to Law [2007], the Negative Binomial distribution can be used as a model for demand since it is only defined for positive values. In contrast to the Poisson distribution which has a fixed variance for a given mean, the Negative Binomial distribution can have different degrees of variance for the same mean. This property makes it more attractive as a model of consumer demand if one wants to investigate the influence of different degrees of demand variability. The degree of variance of NB can be controlled by defining the parameter γ. At high levels of γ NB converges to the Poisson

[1] It is, for instance, more probable that a customer substitutes one brand of butter with another one than giving up on the latest iPod in favor of another brand of MP3 player

distribution with parameter μ_d. For small values of γ, the variance of NB is significantly higher than μ_d (cf. Law [2007]).

The sum of j random variables that are each distributed according to $NB(\gamma, p)$ is distributed according to $NB(j\gamma, p)$ (cf. e.g. Law [2007]). Thus the demand for the considered product at each retail outlet during the sales season is distributed according to $NB(\Delta_{sales}\gamma, p)$. The optimal quantity to be shipped to each outlet before the start of the sales season can be determined using the one period Newsvendor model. Let F_s be the Cumulative Density Function (CDF) of $NB(\Delta_{sales}\gamma, d)$, and let F^{-1}_{sales} be its inverse CDF. Define $f_{sales}(x)$ to denote the Probability Distribution Function (PDF) corresponding to F^{-1}_{sales}. The optimal order quantity according to the Newsvendor model can be computed using Equation 4.3 (cf. Nahmias [2005], p. 244):

$$Q = F^{-1}(\frac{c_u}{c_o + c_u}) \tag{4.3}$$

In Equation 4.3 F^{-1} denotes the inverse CDF of demand, c_u represents the "underage cost" and c_o the "overage cost" per unit. The retailer incurs underage cost if the stocked product quantity does not suffice to satisfy consumer demand. If the consumer demand is higher than the number of available stock, she incurs overage cost. In our model the basic underage cost per item is $c_u = r_R - c_R$ and the unit overage cost is $c_o = c_R - s$. Provided that the demand for the considered product is equal across the n outlets, the optimal batch size shipped to each outlet before the start of the sales season can be obtained according to Equation 4.5.

$$\begin{aligned} Q_0 &= F^{-1}_{sales}(\frac{r_R - c_R}{r_R - s}) && (4.4) \\ &= F^{-1}_{sales}(\frac{m_R}{1 - h(1 - m_R)}) && (4.5) \end{aligned}$$

As we mentioned earlier, the unit RFID tagging cost t is included into the purchase cost, i.e. the optimal order quantity changes accordingly. If products are tagged the optimal order quantity thus changes accordingly and can be obtained according to Equation 4.7.

$$\begin{aligned} Q_1 &= F^{-1}_{sales}(\frac{r_R - c_R - t}{r_R - s}) && (4.6) \\ &= F^{-1}_{sales}(\frac{m_R}{1 - h(1 - m_R)} - \frac{t}{r_R(1 - h(1 - m_R))}) && (4.7) \end{aligned}$$

4.3.1 The Transshipment Algorithm

As outlined in Section 4.2.2 of this chapter, transshipments in retail settings usually have to be of the preventive type in order to be effective. However, in a high-impact product setting customers may also be willing to wait for the satisfaction of their demand – provided that it does not cause too much inconvenience. Therefore fast emergency transshipments from another store that still has the requested SKU in stock can be a viable option. The requested product can either be shipped to the store at which it is most convenient for the customer to pick it up or directly to the customer's home.[2] Such a service may not only increase sales in the short run but may also increase customer loyalty in the long run. In this chapter we consider both preventive and emergency transshipments. The corresponding optimization procedures are described in the following.

Both the preventive and the emergency transshipment policy developed in this chapter are based on information about the statistical characteristics of consumer demand. Since the end of the sales period is known, the expected demand sizes during the time remaining until the end of the sales period can be computed based on the distribution of daily demand.

We assume that transshipments are performed "over night", i.e. outlets with excess stock can transship products to locations with actual or expected shortages in the time between the daily opening hours. The cost of transshipping one unit of stock is c_t.

We assume that preventive transshipments are conducted Δ_{prevTS} days before the end of the product's sales period. Determining the optimal value of Δ_{prevTS} is mathematically difficult. It implies considering the complex trade off between the expected profit changes resulting from the prevention of stock outs that occur until the day of the transshipments and after that day. If Δ_{prevTS} lies closer to Δ_{sales}, more information about the actual demand has already been revealed which increases the effectiveness of transshipments. If the preventive transshipments are conducted earlier in the sales period, the probability that stock-outs which could have been avoided by the transshipments have already occurred becomes smaller. To the best of our knowledge the related literature does not contain any closed form solution for the preventive transshipment problem that is general enough to be applied to our setting. However, since the number of possible values of Δ_{prevTS} is rather small, we were able to determine optimal values using numerical simulation. The optimal transshipment quantities from outlet i to outlet j are determined according to the following algorithm where the scheduled transshipments are

[2]The latter would require that the customer provides her address to the sales person or the store system.

represented by the $N \times N$ integer matrix M_{ij} and I_i denotes the inventory level of outlet i.

Initialize values of transshipment matrix by setting $M_{ij} = 0$ for all i and j;
Repeat:
Determine the sender outlet i with the highest marginal cost $MC_i^{sender}(I_i)$ of maintaining
the current inventory level I_i;
Determine the receiver outlet j with the lowest marginal cost $MC_j^{receiver}(I_j)$ of adding
one item to I_j;
$If(MC_i - MC_j) > c_t$:
Increase scheduled transshipments from outlet i to j by one unit, i.e. $M_{ij} = (M_{ij} + 1)$;
Remove one item from the inventory of outlet i, i.e. $I_i = I_i - 1$;
Add one item to the inventory of outlet j, i.e. $I_j = I_j + 1$;
Otherwise:
Terminate.

We determine the marginal cost $MC_i^{sender}(I_i)$ and $MC_i^{receiver}(I_i)$ using a Newsvendor-style computation. Equation 4.8 provides the total cost function for the single period Newsvendor problem according to Nahmias [2005].

$$C(I) = c_o \int_0^I (I - x) f(x) dx + c_u \int_I^\infty (x - I) f(x) dx \tag{4.8}$$

The variable I denotes the inventory level, c_o and c_u the per unit over and underage cost, and $f(x)$ is the density function of demand. The marginal cost of adding one unit to the available inventory I is the derivative of the total cost function (Equation 4.8). A simplified expression of the marginal cost is provided by Equation 4.11 where $F(x)$ denotes the Cumulative Distribution Function (CDF) of demand.

$$\begin{aligned}
\frac{dC(I)}{dI} &= c_o \int_0^I 1 f(x) dx + c_u \int_I^\infty (-1) f(x) dx && (4.9)\\
&= c_o F(I) - c_u(1 - F(I)) && (4.10)\\
&= (c_o + c_u) F(I) - c_u && (4.11)
\end{aligned}$$

Since the time Δ_{prevTS} that remains until the end of the sales period is known and deterministic, the expected demand during the rest of the sales period can be computed based on the distribution $NB(\Delta_{prevTS}\gamma, p)$ where γ

is provided exogenously and p is obtained according to Equation 4.2. Using Equation 4.11 we can compute the expected cost of adding one unit to the inventory of retail outlet i for the considered setting. Equation 4.12 yields the cost of keeping one unit of stock in the inventory of the sender whereas Equation 4.13 yields the cost of adding one more item to the stock of the receiver. In both expressions $F_{prevTS}(x)$ denotes the CDF of the Negative Binomial distribution $NB(\Delta_{prevTS}\gamma, p)$.

$$MC_i^{sender}(I_i) = (h(1 - m_R)r_R + m_R r_R)F_{prevTS}(I_i - 1) - m_R r_R \tag{4.12}$$

$$MC_i^{receiver}(I_i) = (h(1 - m_R)r_R + m_R r_R)F_{prevTS}(I_i) - m_R r_R \tag{4.13}$$

Emergency transshipments differ in two fundamental aspects from preventive transshipments. Firstly, the demand that can be satisfied via emergency transshipments is certain because customers have already purchased the corresponding products. Secondly, we assume that emergency transshipments can be conducted at the end of each day during the sales period instead of only at one fixed date. The first property simplifies the computation of the marginal cost incurred by receiving outlets. Since each emergency transshipment prevents one lost sale for sure, it simply equals minus one times the unit lost sale cost. The second property changes the demand distribution used for computing the expected marginal cost of outlets that provide stock for transshipment. Since emergency transshipments are evaluated on a continuous basis whenever there is a stock out the corresponding demand distribution changes every day. Let Δ_{emerTS} denote the number of days left until the end of the sales period at the evaluation date and let $F_{emerTS}(x)$ denote the CDF of the Negative Binomial distribution $NB(\Delta_{emerTS}\gamma, p)$. Equation 4.14 yields the cost of keeping one unit of stock in the inventory of the sender whereas Equation 4.15 yields the cost of adding one more item to the stock of the receiver. In both expressions $F_{emerTS}(x)$ denotes the CDF of the Negative Binomial distribution $NB(\Delta_{emerTS}\gamma, p)$.

$$MC_i^{sender}(I_i) = (h(1 - m_R)r_R + m_R r_R)F_{emerTS}(I_i) - m_R r_R \tag{4.14}$$

$$MC_i^{receiver} = (-1)m_R r_R \tag{4.15}$$

4.4 Numerical study

4.4.1 Experimental setup

We have implemented a simulation model of the supply chain described in Section 4.3 in the programming language Java. The generation of random numbers and the required statistical computations were done using the SSJ library for stochastic simulation (cf. L'Écuyer and Buist [2005]). In order to obtain a good overview of the impact of a number of crucial parameters we employed a factorial design. Table 4.1 lists the parameters and corresponding values that were provided as input to the simulation tool. Similar to the

Parameter	Values	Description
r_R	$\{20, 40^*, 60\}$	Unit sales price
m_R	$\{20\%, 30\%^*, 40\%\}$	Percentage retail markup
h	$\{0, 0.2^*, 0.4\}$	Factor of salvage value (cf. Equation 4.1)
c_t	$\{1, ..., 5\}$	Unit transshipment cost
t	$\{0.05, 0.1^*, 0.15\}$	Unit RFID tagging cost
n	$\{2, 6^*, 10\}$	Number of retail outlets
Δ_{sales}	$\{30, 60^*, 90\}$	Duration of sales period in days
μ_d	$\{2, 6^*, 10\}$	Mean daily consumer demand
γ	$\{1000, 5^*, 1\}$	Parameter of the Negative Binomial distribution NB of daily consumer demand

Table 4.1: Model parameters (* indicates default value)

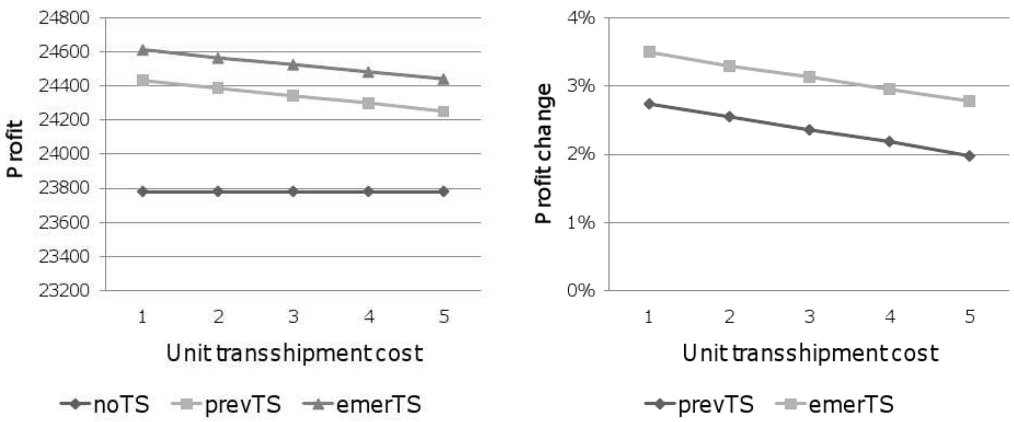
Chapters 2 and 3 the parameter values used in this chapter are geared to the characteristics of high-impact products. The chosen value ranges of the unit sales price r_R and the retail margin m_R reflect the properties of typical high value consumer good such as apparel, electronics, cosmetics etc..
The value range of the unit transshipment cost c_t is geared to typical spot market prices for national packet delivery (e.g. the prices offered on the DHL website).
The parameter range of the daily demand μ_d is based on Atali et al. [2006]. They call a product with a daily demand of 2 "slow moving" and a product with a daily demand of 10 "fast moving".

The simulation procedure has two steps. In the first step the optimal order quantity for the retail outlets was computed using Equations 4.5 and 4.7 respectively. In the case of preventive transshipments we determined the optimal timing of stock balancing by varying the parameter Δ_{prevTS} and observing the effect on the realized profit. In the second step the performance of the supply chain was evaluated for each parameter configuration. In order to ensure the statistical significance of the simulation results, we simulated each supply chain configuration 10,000 times.

4.4.2 Results

To quantify the performance improvements resulting from the implementation of preventive and reactive transshipments we compare three scenarios: The supply chain without transshipments S_{noTS} (the status quo), with preventive transshipments S_{prevTS}, and with emergency transshipments S_{emerTS}. For the initial comparison all model parameters are set to their default values (indicated by * in Table 4.1) while the unit transshipment cost c_t is varied within the specified interval in order to reveal its effect on the performance of the supply chain.

Figure 4.1 shows the profit values obtained for the different scenarios. Both

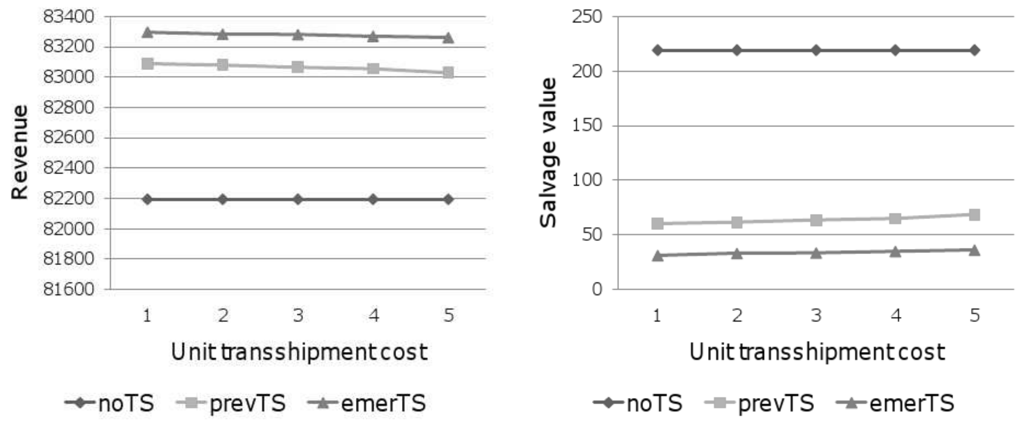


(a) (b)

Figure 4.1: Absolute (a) and relative profit (b) in the different scenarios

preventive and emergency transshipments lead to significant profit improvements within the considered bounds of the unit transshipment cost. For the default configuration the profit improvements vary between 2% and 3.5%. The figures also show that emergency transshipments are more profitable than preventive transshipments.

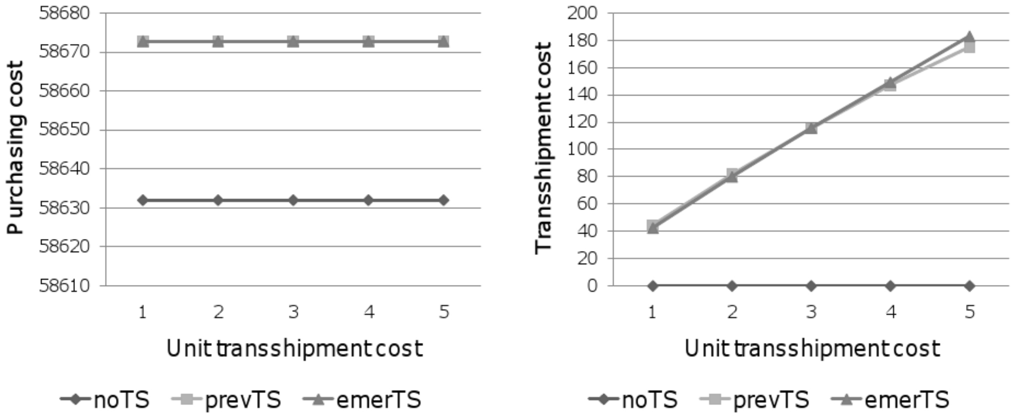
In the following we break down the profit into its different cost and benefit components in order to reveal the reasons for the observed profit outcomes. Figure 4.2 shows the absolute revenue and salvage value earned by the retailer in the different scenarios. Due to its ability to prevent more lost sales, the emergency transshipment policy generates higher revenues than the preventive transshipment policy. The revenue obtained in scenario S_{prevTS} and S_{emerTS} decreases with higher values of the unit transshipment cost. This result can be explained by the trade-off between the lost sale and transship-



(a) (b)

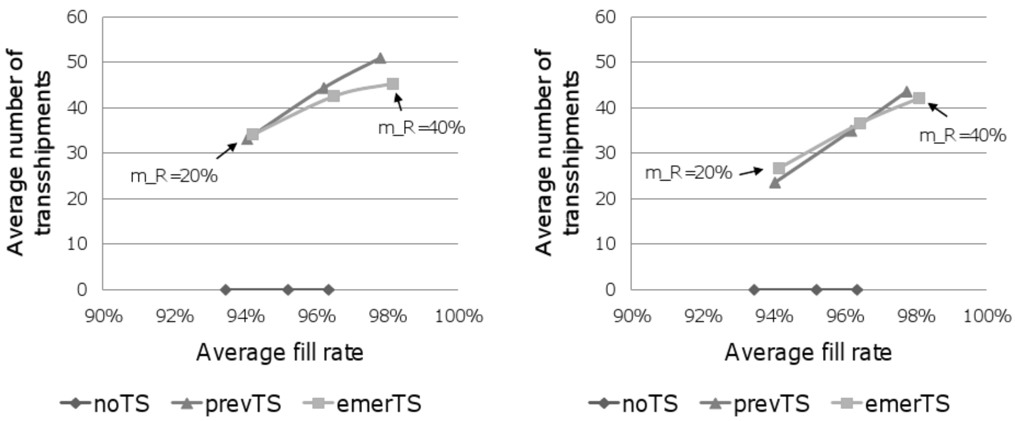
Figure 4.2: Absolute revenue (a) and salvage value (b) in the different scenarios

ment cost. Higher values of c_t make the prevention of lost sales less profitable if the unit lost sale cost $m_R r_R$ remains constant.
Figure 4.3 shows the absolute lost sale and transshipment costs incurred by the retailer in the different scenarios. As indicated by Figure 4.3 (a), the application of the emergency transshipment policy leads to higher purchasing cost than the preventive transshipment policy since we assume that transshipments require item-level RFID tagging. This result is not trivial since the tagging cost t also influences the order quantity negatively (cf. Equation 4.7) which in turn reduces the purchasing cost. However, the effect of t is rather limited if the unit profit $m_R r_R$ is as high as in this study.
As Figure 4.3 (b) shows, emergency transshipments lead to similar transshipment volumes as preventive transshipments.
Figure 4.4 reveals how value is realized in the different scenarios. It shows the trade-off between the average number of transshipments and the achieved fill rate for $c_t = 1$ and $c_t = 5$ at different levels of m_R respectively. The emergency transshipment policy always outperforms the preventive transshipment policy with respect to the fill rate. At higher levels of m_R, i.e. if the economic conditions for transshipments are more favorable, the emergency transshipment policy also needs fewer transshipments on average. This result is not surprising since the emergency transshipment policy has an informational advantage.
In summary, the use of transshipments in the default parameter configuration has a positive effect on the retailer's profit even if unit tagging and transshipment costs are chosen in a conservative fashion. The emergency



(a) (b)

Figure 4.3: Absolute purchasing (a) and transshipment costs (b) in the different scenarios



(a) (b)

Figure 4.4: Trade-off between average number of transshipments and fill rate for $c_t = 1$ (a) and $c_t = 5$ (b) for m_R equal to 20%, 30%, and 40%

transshipment policy is more profitable than the preventive policy because it takes advantage of the certainty about stock-out situations on the receiver side. However, emergency transshipments imply that customers interact with the sales personnel or a computerized front-end and express their willingness to buy and wait for a product.

4.4.3 Sensitivity analysis

To investigate how changes of the model parameters affect the value of transshipments and therefore indirectly the value of item-level RFID, we conducted a sensitivity analysis. We observed the changes to the percentage profit improvements achieved by both transshipment policies in response to individual changes of the model parameter listed in Table 4.1.
Figure 4.5 shows the impact of changes of the retail price r_R on the percentage profit changes. A higher sales price of the considered product positively

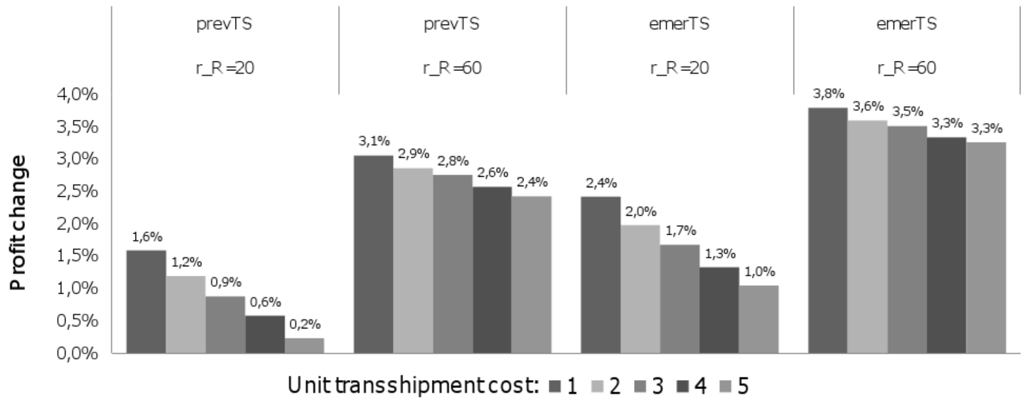


Figure 4.5: Sensitivity of the percentage profit changes with respect to the retail price r_R

influences the lost sale penalty. Therefore transshipments are more profitable at higher levels of r_R.
Figure 4.6 shows the impact of changes of the retail markup m_R on the percentage profit changes when moving from scenario S_{noTS} to scenarios S_{prevTS} or S_{emerTS}. Although an increase of the retail price markup m_R, similar to an increase of r_R, leads to a higher unit lost sales penalty, the impact of m_R on the performance of both transshipment policies is much smaller than the impact of r_R. The reason for this outcome is that increasing m_R not only affects the transshipment policy (cf. Equations 4.12, 4.13, 4.14, and 4.15,) but also the basic order policy. Higher values of m_R cause the order quantity to

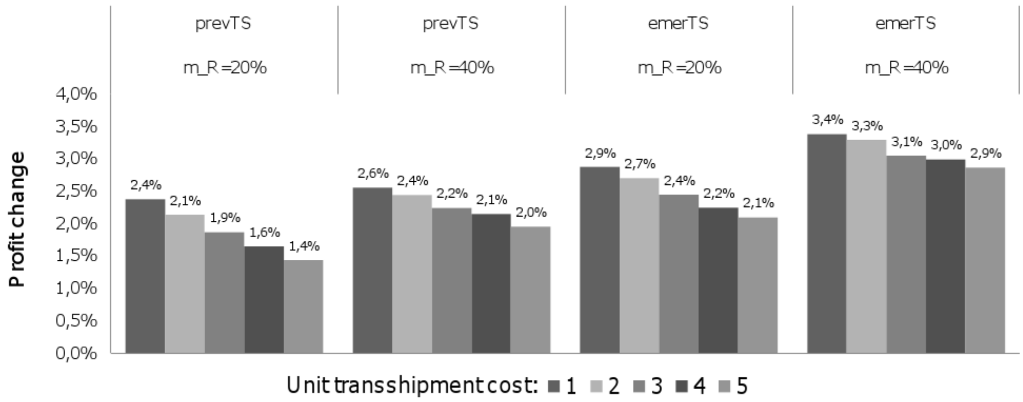


Figure 4.6: Sensitivity of the percentage profit changes with respect to the retail markup m_R

increase (cf. Equation 4.7 and 4.5) which reduces the stock-out probability. This, in turn, limits the effect that the prevention of stock-outs achieved by using transshipments can have.
Figure 4.7 shows the influence of the parameter h on the percentage profit improvements realized by the transshipment policies. As the figure reveals,

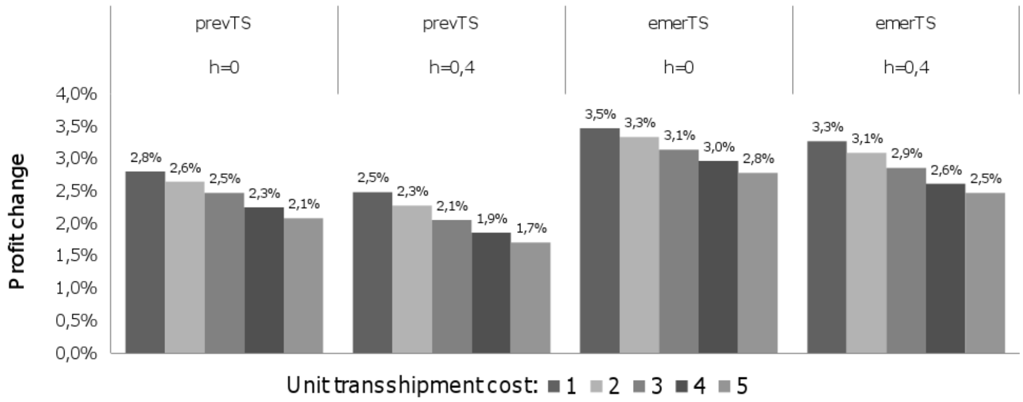


Figure 4.7: Sensitivity of the percentage profit changes with respect to the retail price h

this influence is rather small. Similar to the retail markup m_R, the salvage cost factor h influences both the transshipment decision and the order decision. An increase of h causes the order quantity to increase which lowers the stock-out probability. This effect compensates the increased per unit value of preventing lost sales via transshipments.
Figure 4.8 shows the impact of changes of the unit RFID tagging cost t on

the percentage profit changes when moving from scenario S_{noTS} to scenarios S_{prevTS} or S_{emerTS}. Although the use of transshipments within the consid-

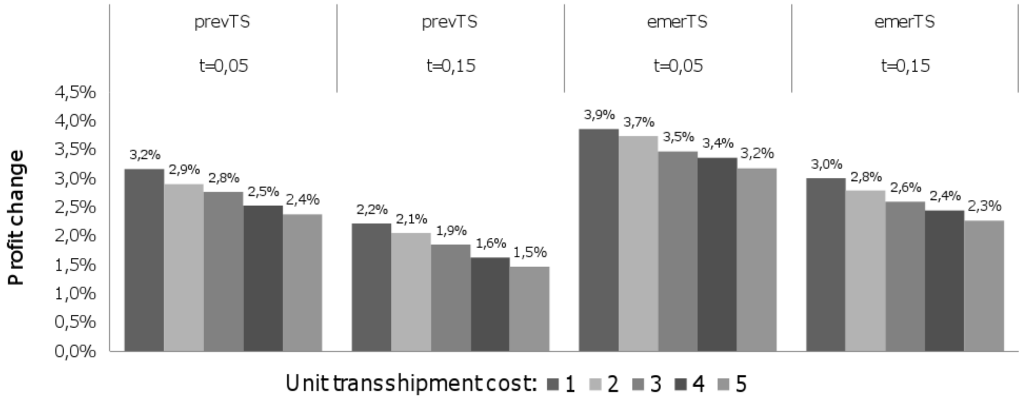


Figure 4.8: Sensitivity of the percentage profit changes with respect to the number of retail outlets t

ered bounds of the unit tagging cost remains profitable, the variation of t has a strong impact.
Figure 4.9 shows the impact of changes of the number of retail outlets n on the percentage profit changes when moving from scenario S_{noTS} to scenarios S_{prevTS} or S_{emerTS}. The number of retail outlets participating in the trans-

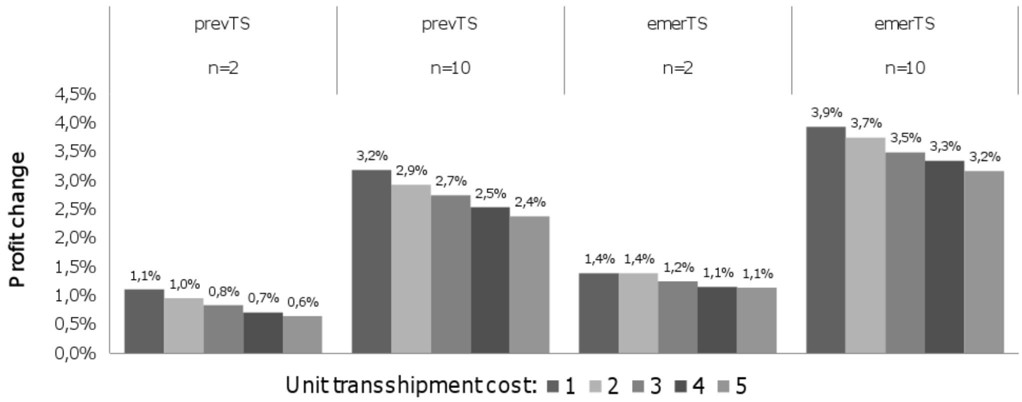


Figure 4.9: Sensitivity of the percentage profit changes with respect to the number of retail outlets n

shipment operations has a positive impact on the value of transshipments. This effect corresponds with a well-known result from the supply chain management literature, namely that increased inventory pooling increases the

responsiveness of supply chains (cf. e.g. Chopra and Meindl [2004]). Since transshipments do exactly that, their value increases with the degree of inventory dispersion across different stores.
Figure 4.10 shows the impact of Δ_{sales}, i.e. the duration of the sales period, on the percentage profit improvements achieved by transshipments. As the

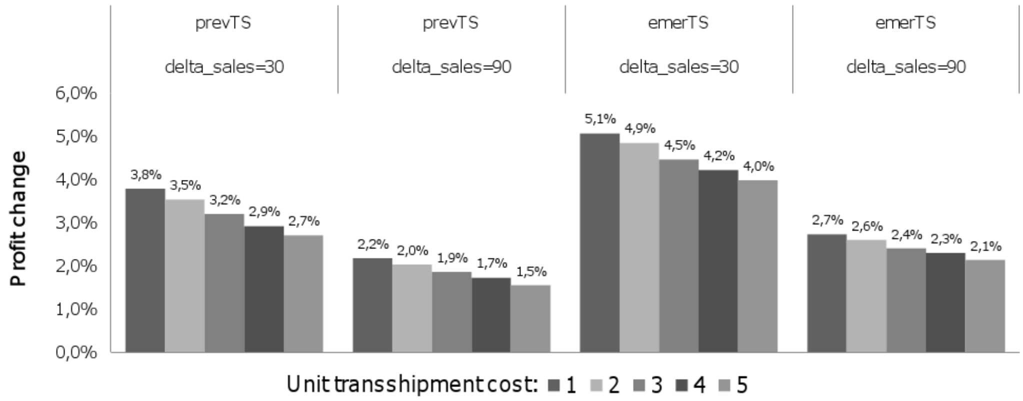


Figure 4.10: Sensitivity of the percentage profit changes with respect to the duration of the sales period Δ_{sales}

figure reveals, the duration of the sales period has a negative impact on the value of transshipments. This result is due to the fact that the coefficient of variation of the probability distribution NB describing the sum of random variables is lower than the coefficient of variation of the distributions describing the single random variables. Thus, the longer the sales period, the lower the demand risk provided that the daily demand distribution are equal. Since transshipments help to increase the responsiveness of a distribution system facing uncertain demand, they yield more value if the variability of demand is higher, i.e. if Δ_{sales} is shorter (cf. also Figure 4.12).
Figure 4.11 shows the impact of changes of the mean daily customer demand μ_d on the percentage profit changes when moving from scenario S_{noTS} to scenarios S_{prevTS} or S_{emerTS}. It demonstrates that μ_d has a negative impact on the value of transshipments. This outcome can be explained by the fact that the coefficient of variation of the daily demand is higher for smaller values of μ_d. The higher demand uncertainty resulting from a larger value of μ_d in turn has a negative effect on the supply chain's profit in scenario S_{noTS}. Since transshipments allow for increasing supply chain responsiveness, they have a higher impact if the mean daily demand is lower.
Figure 4.12 shows the impact of changes of to the parameter γ on the percentage profit changes induced by transshipments. The parameter γ, together with the mean daily demand μ_d and the duration of the sales period Δ_{sales},

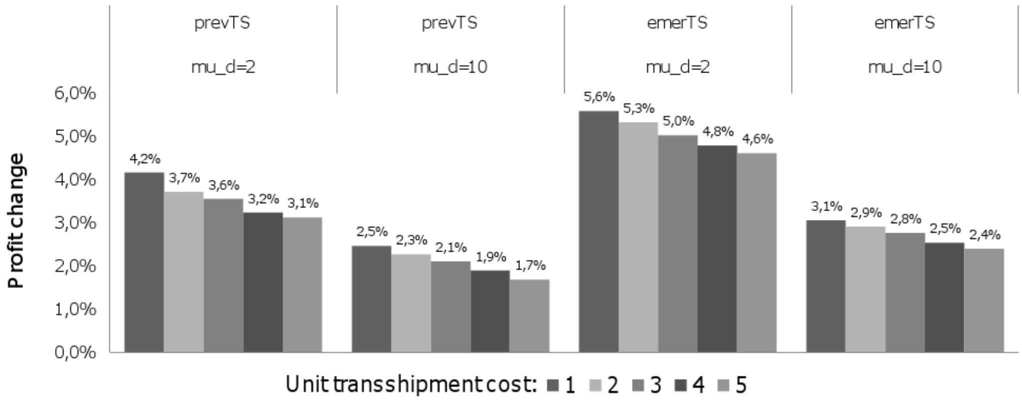


Figure 4.11: Sensitivity of the percentage profit changes with respect to the mean daily customer demand μ_d

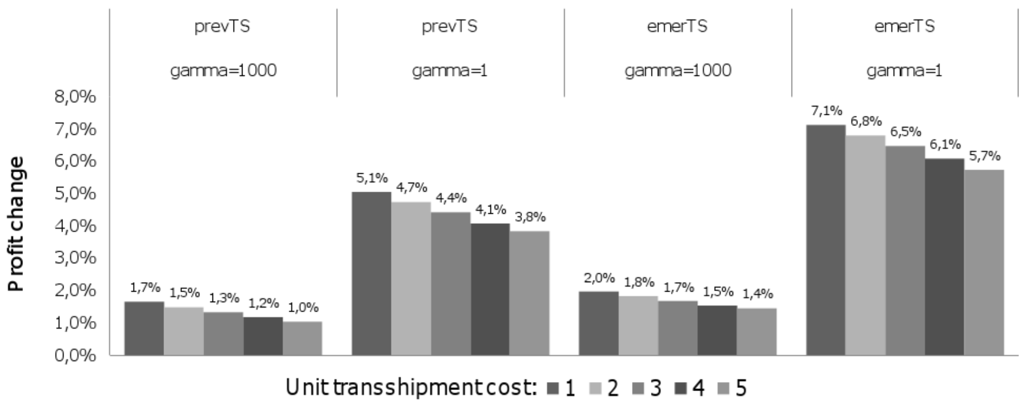


Figure 4.12: Sensitivity of the percentage profit changes with respect to the mean daily customer demand γ

determines the degree of demand uncertainty. Lower values of γ translate into higher demand uncertainty. Higher demand uncertainty in turn reduces the profit of the supply chain in the status quo and thus increases the value of practices that help to reduce its exposure to demand risk such as transshipments.

In summary, the sensitivity analysis has shown that transshipments always lead to a significant performance increase. The size of the performance increase, however, crucially depends on parameters defining the supply chain setting. The retail price r_R, the price markup m_R, the number of retail outlets n, and the variance of demand expressed by the parameter γ have a positive impact on the value of transshipments whereas the salvage cost factor h, the duration of the sales period Δ_{sales}, the size of the daily demand μ_d, and the tagging cost t have a negative impact on the value of transshipments.

4.5 Conclusion

Item-level transshipments are an innovative operational practice that can increase the responsiveness of a supply chain. A basic precondition for their efficient use is that the unit lost sale cost is higher than the unit transshipment cost. As our numerical results have shown, the profitability of transshipments is higher the more pronounced the innovative characteristics of a product are, i.e. high demand uncertainty, short sales periods, high value, high margin, etc. (cf. Lee [2002]). We have investigated both the value of preventive and emergency transshipments. Preventive transshipments are less profitable than emergency transshipments but do not require additional interaction of the sales personnel and the customer. In particular, the implementation of emergency transshipments implies that the customer explicitly requests the transshipment of a product.

To date, item-level transshipments are not common practice in retail environments. Although a number of researchers have investigated their advantages and have found significant potential, most practitioners are skeptical about their applicability in the real world. In particular, they often mention two reasons complicating their adoption.

Firstly, item-level transshipments require accurate data about the number of products available in each retail outlet that belongs to a transshipment group. Unfortunately, store-level inventory records are often inaccurate in practice, especially the ones of products that are more likely to shrink (e.g. due to theft or spoilage). Accurate inventory levels are not only a precondition for the effective working of transshipment operations, they may also

have a detrimental effect on customer satisfaction. In the case of emergency transshipments, for instance, a retailer must be absolutely sure that a product is actually available at another store if she promises its delivery to the customer.
Secondly, item-level transshipments are only profitable if they can be conducted quickly and efficiently. In order to be of any use, preventive transshipments should be feasible within a day or less and should not cause excessive labor costs.

The advent of item-level RFID could fundamentally change the ROI of transshipments in retail. On the one hand, this technology allows for increasing the accuracy of inventory records to 100% which removes the first adoption barrier mentioned above. On the other hand, it allows for new ways to save time and cost in picking, packing, shipping, and receiving activities. Provided the access to accurate real-time information about the position of products in the store, the conception of IT systems that automatically generate directions for the store personnel and guarantee that the correct SKUs are picked in the right quantities is possible. Although the practical feasibility of such systems still has to be evaluated in the specific context of item-level transshipments, their potential in general picking processes has repeatedly been confirmed in practice. Automated picking lists and pick-by-light systems have already successfully applied in warehouse settings and could easily be adapted to the retail store setting.

Instead of analyzing the information value of item-level RFID directly like in the previous Chapters of this dissertation, we have investigated the performance gains resulting from a supply chain practice that can be enabled by this technology in this chapter. Similar to the findings of Chapter 2 and 3 we could again observe that the value of item-level RFID, here exemplified by the value of the transshipment practice it may enable, is significantly higher for products with innovative characteristics and thus also for the high-impact products we focus on in this dissertation.

The profit metric considered in our analysis only includes the obvious variable costs. Fixed costs associated with the use of RFID transponders include the purchase and/or operation of the required RFID reader infrastructure at the retail outlets which are shared across all tagged products. Those fixed costs were left aside since our assumptions do not allow for estimating the number of readers, service hours, etc.. However, since these costs can be estimated with relative ease as soon as the usage scenario and technical requirements have been specified, their sum can simply be compared with the

benefits that can be computed using our approach.
We have demonstrated that within the considered interval of the unit transshipment cost (1 to 5 Euros), item-level transshipments of rather high value products (sale prices greater or equal to 20 Euros) make economic sense even if the full tagging cost (between 5 and 15 Eurocents) is subtracted from the net benefit. As we have shown in the previous Chapters of this dissertation, item-level RFID provides other benefits that add up to the benefits investigated in this Chapter.

Chapter 5

The Role of Information Sharing in Vertical Integration Strategies – Empirical Insights from the Apparel Industry

5.1 Introduction

The business success of "fast fashion" companies like H&M, Mango, or Zara has attracted the interest of practitioners and researchers worldwide. Whereas many traditional apparel retailers struggle with shrinking demand and cost pressure, the revenues and store networks of fast fashion retailers have been expanding steadily. According to industry experts, these companies obtain their competitive advantage from a unique capability of translating fashion trends into affordable products and delivering them in a timely manner. This capability enables them to serve the market better than most incumbent fashion retailers, in particular traditional department stores that once dominated the retail of clothing. The emergence of fast fashion companies is also fueled by changes in consumer behavior. On the one hand, consumers increasingly long for choice and are becoming more fashion-savvy. Fashion executives feel a constant pressure to quickly pick up the latest trends and supply clothing that adheres to them (cf. The Economist [2005]). On the other hand, the customer segments that are most interesting from a business perspective (like young women) often behave highly price sensitive. Amidst these trends, the share of expenditures consumers spend on apparel has been going down (OECD [2009]). Together these trends result in increasingly stiff competition on the apparel market.

Attracted by the rapidly growing market share of fast fashion retailers, many traditional apparel companies are searching for ways to remain competitive. For many of them, improving business performance is a matter of survival: traditional clothing retailers, including major department store chains, are suffering from steadily shrinking margins. Their suppliers - apparel companies that own brands and manufacture garments - are facing a dilemma as well. On the one hand, the retailers that they are selling their products to shield them against demand uncertainty: wholesale orders are usually fixed before production begins. On the other hand, the problems of incumbent retailers facing fast fashion companies also affect their competitive position in the long run. Defining a strategy that preserves their competitiveness is a complex task for these companies. Radical changes of the business model are risky because they imply adding operations that management has no experience with, such as selling products directly to consumers. In spite of such risks, an increasing number of apparel brand owners have started to exert more control over how their products are being marketed. In their attempt to mimic the success of fast fashion retailers, brand owners have launched their own shops, started franchising businesses, and devised shop-in-shop solutions for department stores. All these measures are directed at increasing their control of the distribution channel.

Many questions remain, however, regarding strategies to keep traditional brands competitive. A closer look at the management practices and organizational features of fast fashion retailers reveals at least two differences compared to traditional retailers: *vertical integration*, and *intensive information sharing* between the manufacturing and retailing stage of the supply chain.

In the traditional apparel supply chain, brand manufacturers are responsible for the design and manufacturing of products, whereas specialized retailers sell the garments to consumers. This division of tasks has the advantage that each company can concentrate on its core competencies: while brand manufacturers apply their design and production know-how, retailers use their marketing expertise for presenting and selling different brands. In contrast to this, the typical fast fashion company steers the whole apparel supply chain. It controls the design, manufacture, marketing, and distribution of its own brands. Ferdows et al. [2004] claim that the vertical integration of industry champions like Zara and H&M and the resulting control over the supply chain are the key to their success.

In this work we hypothesize that the vertical integration observed in the apparel industry is an enabler for value-generating management practices rather than the direct cause of superior performance. Apparel companies that own, or at least control, the entire supply chain are more likely to obtain accurate and timely analytics (e.g. on sales and inventories) and thus have an informational advantage. Porter [1980] points out that superior marketing intelligence is one of the outstanding advantages of vertical forward integration. Our interviews with industry insiders as well as earlier case study research support this hypothesis. For instance, Zara's global store network can be conceived as a giant data collection device. The point-of-sale data is transmitted by hundreds of stores to headquarters on a daily basis. This information enables detailed sales trend analyses and triggers design and production processes without significant delay (cf. Ferdows et al. [2004]). Although this is only possible by taking advantage of information technology solutions, Ferdows et al. [2004] suggest that at least Zara is not a first mover when it comes to IT investments. More important in their view are standardized information sharing processes and a culture of effective communication. For instance, at the end of each business day, store managers compile a detailed sales report that allows decision makers at headquarters to evaluate the success of certain products. When a new fashion trend is identified, the size of the corresponding production lots can be increased to meet future demand.

In this paper, we investigate the impact of vertical integration and information sharing practices on the performance of apparel supply chains. We focus on the relationship between the degrees of control that brand manufacturers are exerting over the sale of their products and the intensity of information sharing between the manufacturing and retail part of the supply chain. Our central hypothesis is that vertical integration is positively related to performance because it enables more intensive information sharing along the supply chain, which in turn improves performance. We test our hypotheses using a data sample from the German apparel industry.

In the next section we provide an overview of related work, followed by the presentation of our hypotheses and a conceptual model. Subsequently we describe the employed methodology and the results of an empirical study with the apparel companies operating in the German market. At last we discuss our findings and derive managerial implications.

5.2 Related Work

Vertical integration is usually equated with the concentration of ownership of facilities and assets (Grossman and Hart [1986]), the organization of activities (Riordan [1990]), or the control of activities (Reve [1990]) in successive stages of the supply chain in the hands of a single organization (Richardson [1996]). Both Reve [1990] and Williamson [1988] use the notion of vertical integration as a quasi-continuous range with full integration through ownership at one end, and arms-length market exchange at the other - a view adopted in this work. Zara, for instance, can be considered to be highly vertically integrated since it owns a large part of the manufacturing and distribution facilities as well as a dedicated store network. The general literature on vertical integration is massive and can only be sketched here. According to Klein [2004], there are two main streams of literature on vertical integration: a more traditional one that views vertical integration as an attempt to earn monopoly rents by gaining control over input markets and distribution channels, and the transaction cost approach introduced by Coase [1937] that views vertical coordination as an efficient means to protect relationship-specific investments or to mitigate other potential conflicts under incomplete contracting. Coase [1937] first explained that the boundaries of organizations, among other things, depend on transaction cost trade-offs. A market-based organization of the supply chain, which in the case of the apparel industry involves the traditional sharing of tasks among clothing manufacturers, brand owners and retailers, entails certain costs: discovering the relevant prices, negotiating and enforcing contracts, etc.. Within a vertically integrated firm, such external transaction costs should be smaller in relative terms because the related activities are coordinated by a central authority that at least theoretically has unambiguous goals. However, centralized coordination also brings internal transaction costs, namely problems of incentives, monitoring, and performance evaluation. Coase [1937] argues that the boundary of the firm is determined by the trade-off, at the margin, between the relative transaction costs of external and internal exchange (Klein [2004]).

One potential advantage of vertical integration in the transaction cost context is the alignment of incentives at the firm level (Williamson [1971], Williamson [1975]): the unilateral integration of successive supply chain stages - be it in the form of acquisition, or by more subtle ways of transferring control - helps to reduce the generic conflicts that exist in supply chains consisting of several independent organizations. Those conflicts arise from the fact that the interests of the firms controlling different stages of the supply chain can be misaligned. A typical example for the suboptimal outcomes caused by such incentive misalignments is double marginalization (Spengler [1950]): retailers often make order decisions that do not optimize the overall supply chain profit because they do not account for the supplier's profit margin. Other examples of negative spill-over effects include retailers that undermine a supplier's promotion effort by opportunistically overstocking (cf. e.g. Clemons and Row [1993]). In theory, such conflicts should not exist in a vertically integrated supply chain because it is controlled by one organization that follows non-contradicting goals. In practice, conflicts of interest between feuding divisions within an enterprise may still exist and need to be overcome.

Another source of potential conflict arises from the information asymmetries that are inherent to supply chains in connection with misaligned incentives (Williamson [1971], Williamson [1975]). Due to their different roles in the supply chain, manufacturers, retailers, and other participating organizations possess proprietary information about demand conditions, products, and supply chain operations. This opens up room for opportunistic behavior because one party can take advantage of its private information to obtain advantages at the expense of another party; or it can exploit the incapability of the other party to obtain certain information, again by acting in a way that is advantageous for it but not for the other party. The economics literature classifies conflicts caused by asymmetric information into "adverse selection" and "moral hazard" types of situations, depending on whether the information discrepancy plays a role before or after decision making (Laffont and Martimort [2002]). A typical example for the effect of information asymmetry in the supply chain is the bullwhip effect, where downstream companies exaggerate demand forecasts in order to reduce their risk to be out of stock (Terwiesch et al. [2005]). Again, vertical integration can be a solution since it has the potential to eliminate firm-level incentives for information hiding. It may thereby trigger the adoption of information systems that help to consolidate accurate and timely data from different stages of the supply chain.

When speaking of opportunistic behavior, the notion of trust gains importance. Although the diverse perceptions of how trust influences interaction complicate its definition, recent empirical studies have begun to operationalize and integrate the concept of trust into a transaction cost framework. Dyer and Chu [2003], for instance, find empirical evidence that a high degree of trustworthiness between supply chain participants reduces transaction costs and improves information sharing. Handfield and Bechtel [2002] perceive the creation of trust in supply chain relationships as a substitute of vertical integration, thus implying that both can be applied to increase performance in the face of high transaction costs.

Klein et al. [1978] and Williamson [1979] point out, transaction costs due to opportunistic behavior are fueled by asset specificity, low transaction frequency, and uncertainty associated with the transactions in question. Fashion apparel is far from being a commodity. Orders are placed rather infrequently (mostly once per product life cycle), and demand for apparel is often highly uncertain. The apparel supply chain therefore seems a good candidate for vertical integration, according to the transaction cost approach. Nevertheless, the consensus in the general literature on vertical integration is that it is less advantageous in 'volatile' environments, e.g. markets characterized by high demand uncertainty such as fashion (Richardson [1996]). Vertical integration in such environments is expected to limit flexibility and information about input and product markets because vertically integrated firms are more isolated (Harrigan [1983]). It is thought to create an inflexible commitment to assets and capabilities at risk of losing their value as circumstances change (Teece [1992]). However, both Harrigan [1983] and Porter [1980] concede that the integration of manufacturing firms into retail may have its advantages, in particular with regard to market intelligence and differentiation. In fashion retailing, the mentioned advantages are obviously important: immediate feedback from retailers about what sells where is crucial for the efficient control of marketing, production, and distribution activities. Differentiation certainly plays an equally important role: store appearance, sales service, and local marketing efforts are an important means for differentiation in apparel retail.

The benefits of providing demand information to higher supply chain stages in a timely and accurate manner have been shown by various authors, both analytically and empirically. An excellent review of recent literature on the use of information sharing mechanisms in supply chains and their implications has been provided by Sahin and Robinson [2002]. Analytical models include the one by Fisher and Raman [1996] that focuses on fashion retailing. Other authors analyze more general supply chain models, mostly with an emphasis on explaining the so-called "bullwhip effect" and proposing demand information sharing schemes as countermeasures (e.g. Lee et al. [1997]). Empirical studies on the value of information sharing in supply chains in general include Li and Lin [2006] as well as Zhou and Jr. [2007]. The authors of both studies conclude that information sharing has a strongly positive impact on supply chain performance.

The need to share large quantities of data has lead to an intensive use of information technology for managing supply chains. In particular, the quick response (QR) initiatives in the textile and apparel industries have spawned the usage of more advanced information systems supporting the order management cycle (Forza and Vinelli [1997]). The information exchanged electronically includes production orders and administrative documents, such as invoices and delivery notes, i.e. information that is absolutely essential. The use of dedicated information technology to generate and process the related data has increased efficiency by saving time. Apart from administrative documents, the information that is exchanged using supply chain information systems may also include dynamic logistics and commercial data such as price lists, material availability, sales levels, and stock levels (cf. Forza and Vinelli [1997]). This type of information is not absolutely necessary for the basic functioning of the supply chain but it can enable better coordination and enhance performance. Whereas the electronic exchange of the first type of information has a clear operational focus, the second type also has a strategic dimension: the theoretical results outlined above suggest that the decision to share certain data related to supply and demand levels may be advantageous or disadvantageous depending on the situation. For instance, if an apparel retailer has no sufficient stock to fill the orders of all its retailer customers, it has to select the customers it wants to serve; granting the customers access to its inventory management system would make such rationing decisions transparent. Very likely, the apparel manufacturer would not be interested in this outcome because it would limit its flexibility in revenue management. Similar examples can be constructed with regard to the demand side; e.g., retailers may refrain from providing detailed point-of-sale (POS) data to the apparel brand manufacturers because they fear interference with their way of marketing and selling from their side. In fact, since apparel brand manufacturers often devise marketing strategies that place restrictions on the way of selling their products (e.g. regarding their price, display time, presentation, etc.) they have an incentive to monitor the retailer's activities. Since item-level RFID enables retailers to collect such information, it could represent a crucial enabler of vertical integration strategies.

We contribute to existing research on vertical integration and information sharing in supply chains by integrating the central hypotheses from both research streams in one conceptual model: the hypothesis that vertical forward integration improves performance of apparel supply manufacturers (Richardson [1996]), and the hypothesis that more intensive information sharing in supply chains leads to better business performance (cf. e.g. Lee [2002], Li and Lin [2006], Zhou and Jr. [2007]). Since there exists a number of organizational practices popular in the apparel industry that are supposed to increase the control over sales activities but do not imply the ownership of facilities and assets (e.g. franchises, shop-in-shop solutions, concessions), our definition of vertical integration slightly differs from the definitions used in other publications. By measuring the degree of vertical forward integration, the intensity of information sharing, and the performance of the apparel manufacturer or brand owner, we are also able to test the hypothesis that vertical integration has a significant positive impact on performance because it enables more advanced information exchange: in this case the intensity of information sharing is hypothesized to *mediate* the relationship between vertical forward integration and performance. The theoretical background given above provides a basis for this hypothesis and indeed it is supported by the empirical findings presented in the next section. To our knowledge, there has been no empirical study so far that investigates these relationships.

5.3 Hypotheses and Conceptual Model

Our conceptual model is made up of four interdependent hypotheses referring to three conceptual constructs: *Vertical Forward Integration* (VFI), *Intensity of Information Sharing* (IIS), and *Performance of Brand Manufacturer* (PBM). The exact meaning of these constructs as well as our hypotheses will be described in the following.

The impact of information sharing on business performance has been tested in various empirical studies (e.g. Li and Lin [2006], Zhou and Jr. [2007]), albeit not in our specific context. Analytical research in the area of supply chain management also comes to the conclusion that demand uncertainty has a positive impact on the profitability of information sharing (Lee et al. [1997]). In line with these theoretical and empirical results, Ferdows et al. [2004] conclude that intensive information sharing is particularly important in apparel supply chains since these have to cope with highly volatile demand. We therefore hypothesize:

Hypothesis 1

The intensity of Information Sharing (IIS) between brand owner and retailers is positively related to the Performance of the Brand Manufacturer (PBM).

Our second and third hypotheses refer to the impact of vertical integration. According to Grossman and Hart [1986] a firm is vertically integrated if it owns facilities and assets. This definition constitutes the extreme of vertical integration. However, measuring vertical integration only in terms of ownership does not adequately represent the reality in the apparel industry where manifold practices for increasing the control of one supply chain participant over the other have evolved. We focus on a special type of vertical integration, namely the *Vertical Forward Integration* of brand manufacturers into retail. *Vertical Forward Integration* refers to all measures taken by the brand manufacturer to increase control over the sales activities of the retailers, which does not necessarily include the acquisition of facilities and assets (Richardson [1996]). This definition is compatible to the common understanding of the term vertical integration in the apparel industry. Whereas Zara, Mango or H&M certainly mark the extreme on the vertical integration scale, most brand owners are somewhere in between: they neither own all points of sale nor do they act like traditional clothing manufacturers who exert no influence on sales activities at all. The fast fashion challenge has led to the development of a broad spectrum of models that increase the apparel manufacturers' control of the retailing of their brands, including multi-channel sales (i.e. starting a direct sales channel while maintaining a wholesale channel), concessions (i.e. contractual agreements that allow apparel companies to rent shop floor from specialized apparel retailers), as well as shop-in-shop solutions (i.e. the presentation of apparel products of a certain brand in a dedicated area that is arranged according to the specifications of the brand owner).

Although the literature does not support the view that vertical integration is particularly advantageous in uncertain business environments like fashion apparel, vertical forward integration may yield some specific benefits due to superior market intelligence and differentiation (Harrigan [1983], Porter [1980]). Furthermore, agency theory predicts that in situations where incentives are misaligned and information asymmetries exist, market-based interaction may produce suboptimal outcomes due to the expectation of opportunistic behavior (Laffont and Martimort [2002]). Since vertical integration transfers control to one organization, it reduces the incentives for information hiding and misrepresentation on the firm level. We therefore hypothesize:

Hypothesis 2

Vertical Forward Integration (VFI) is positively related to the Intensity of Information Sharing (IIS) between brand owner and retailers.

The positive connection between the vertical forward integration and business performance in the apparel sector is intensively discussed by Richardson [1996], although not tested empirically. Extending his study we hypothesize:

Hypothesis 3

Vertical Forward Integration (VFI) is positively related to the Performance of the Brand Manufacturer (PBM).

Hypothesis 4 summarizes the relationships described above (Hypotheses 1-3) and is central to our work. It states that the positive influence of vertical integration in the apparel industry is largely due to the improved information flow it enables. We hypothesize:

Hypothesis 4

The expected positive influence of Vertical Forward Integration on the Performance of the Brand Manufacturer is mediated by the Intensity of the Information Sharing between the apparel brand owner and the retailers.

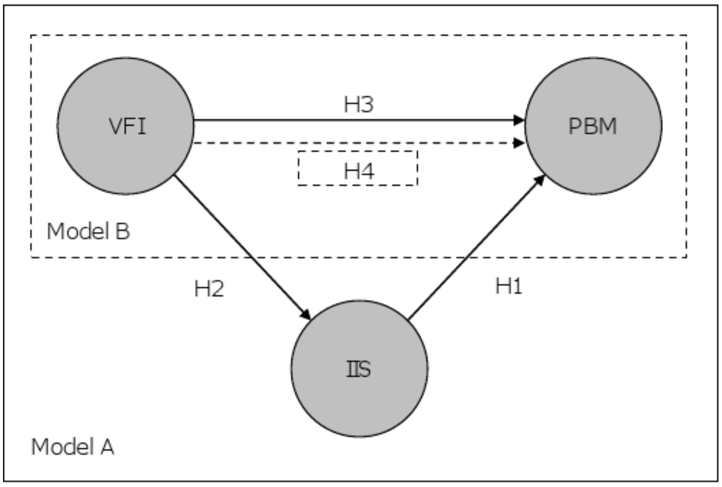


Figure 5.1: The conceptual model

Figure 5.1 summarizes the hypotheses into a conceptual model (Model A). Additionally, in order to prove Hypothesis 4, the alternative Model B, consisting of a simple direct link from the *Vertical Forward Integration* to the *Performance of the Brand Manufacturer*, is tested as explained in the following section.

5.4 Empirical Analysis

5.4.1 Survey Design and Sampling

We developed a survey instrument to capture the *Vertical Forward Integration*, *Intensity of Information Sharing*, and the *Performance of the Brand*

Manufacturer constructs as well as some descriptive statistics. Ahead of the survey, several industry experts and representatives were interviewed, partly in person, partly by phone. The interviews served to gain a better understanding of the drivers of the current vertical integration trend in the apparel industry as well as to fulfill formal requirements. In particular, the survey questions were discussed one by one to ensure the content validity of the measured constructs. This procedure also ensured that the terms used in the survey were clear and equally interpreted by the practitioners.

As a second step, general contact details and company descriptions of 350 medium and large-sized apparel manufacturers (brand manufacturers) operating in Germany were extracted from various publicly available databases. Those companies were contacted by phone in order to identify a competent contact person (usually the head of logistics or marketing). Finally, 307 verified contacts were asked for participation in a standardized online questionnaire per mail and phone. The data collection effort was finished in winter 2008 resulting in 57 usable data points. Thus, the response rate constituted 18.6%. The survey was conducted in an anonymous manner to encourage participants to honestly answer the questions. In order to evaluate the representativeness of the sample, we analyzed its distribution with respect to four basic company profile indicators: size of revenue, number of employees, product life cycle, and price segment of goods sold, as shown in Table 5.1. None of the four indicators exhibits any unexpected concentration which would be an indication for insufficient representativeness of the data set. Since the manufacture of apparel is dominated by companies most of which are not legally obliged to publish business reports, a formal analysis of the representativeness of the data sample based on quantitative data is hard. However, according to the fashion executives interviewed, the sample at hand represents the brand owner side of the German apparel market fairly well.

5.4.2 Measurement Scales

The three constructs which our hypotheses are based on - *Vertical Forward Integration*, *Intensity of Information Sharing*, and *Performance of the Brand Manufacturer* - were measured using multiple indicators. These indicators formed the corresponding measurement scales. All items were anchored on the 5-point scale shown in Table 5.2. In addition, participants were given the opportunity to select a "not applicable" option for each statement in a

Table 5.1: Sample characteristics

Revenues in Million Euro	% of companies	Employees	% of companies	Number of assortments per year	% of companies	Price Segment	% of companies
< 50	21.05%	< 200	29.80%	1 or 2	19.30%	low price	14.00%
$50 - 100$	26.32%	$200 - 500$	35.10%	3 or 4	35.10%	medium price	57.90%
$101 - 200$	17.54%	$501 - 1,000$	8.80%	> 4	36.80%	high price	24.60%
> 200	17.54%	$> 1,000$	15.80%				

survey. All constructs in the model have been modeled as reflective based on the authors' best judgment. To ensure the reliability of the results, another model was tested with *Vertical Forward Integration* being modeled as formative. The result of this evaluation was qualitatively similar with regard to path significance and relationship direction. This test allowed us to verify that the results obtained are indeed a reflection of the existing situation and not an outcome of the chosen modeling approach.

In accordance with our definition of *Vertical Forward Integration*, the items we used to operationalize the corresponding construct reflect the degree of control exerted by the brand manufacturer over sales activities of the retailers. Initially based on Etgar [1977], the items were reworked in cooperation with the industry experts to fit the context of the apparel business.
The scales used to measure the *Intensity of Information Sharing* construct were partly adapted from the work of Li and Lin [2006]. They cover completeness, detail, timeliness, and reliability of the information sharing activities between the retail and the brand owner.
The items of the *Performance of the Brand Manufacturer* construct were drawn from the pool of the items already available from Bhatnagar and Sohal [2005], Mattila et al. [2002], and Hallén et al. [1991]. All performance metrics were chosen on the basis of the industry experts review to fit the targeted industry but are sufficiently general to allow for comparability.

Latent Variable	Item	Item Text
Vertical Forward Integration	Intro	To what extent do you agree with the following statements concerning your control possibilities with regard to retailers? (5-point scale, strongly disagree - strongly agree)
	VFI_1	We recommend retail prices for our products.
	VFI_2	We exert influence on the minimum order sizes of retailers.
	VFI_3*	We share advertising costs with the retailers.
	VFI_4	We exert influence on the way our products are presented in the retail stores.
	VFI_5*	We exert influence on the staffing policy of the retail shops.
Intensity of Information Sharing	Intro	To what extent do you agree with the following statements concerning the information exchange with the points of sale (customer and/or own stores)? (5-point scale, strongly disagree - strongly agree)
	IIS_1	We inform our points of sale about relevant changes regarding supply and demand and vice versa.
	IIS_2	The information exchange between us and our points of sale involves more than just order data, e.g. inventory levels, POS data, and planning data.
	IIS_3	We work closely with our points of sale regarding information exchange on sales and delivery scheduling.
	IIS_4	The information exchanged between us and our points of sale is transmitted in a timely manner.
	IIS_5	The exchanged information is detailed.
	IIS_6	Information exchange is reliable.
Performance of the Brand Manufacturer	Intro	Please compare the average performance of your company in the last 3 years with the industry average. (5-point scale, much worse - the same - much better)
	PBM_1	Return on Investment (ROI)
	PBM_2	Development of the market share
	PBM_3	Revenue growth
	PBM_4	Profit growth
	PBM_5	Overall performance
	PBM_6*	Logistics costs

* item was removed during the model adjustment process.

Table 5.2: Measurement Scales

5.4.3 Statistical Methodology

The estimation of the structural equation model (SEM) presented in Figure 5.1 can be done on the basis of two conceptually different approaches: the analysis of covariance (Jöreskog [1977]), or the analysis of variance, also referred to as the partial least squares (PLS) analysis (Wold [1982]). In this study we evaluate our model using PLS mainly because this is the method of choice if the cause-effect relationships of the underlying conceptual model constitute only vague assumptions as in our case. Furthermore, whereas the covariance-based approach requires a minimum of 200 observations (Boomsma and Hoogland [2001]), Barclay et al. [1995] suggest that the required sample size for using PLS should be at least ten times the number of exogenous constructs having an impact on the most complex endogenous construct, which amounts to a minimum of 20 observations in our case. With 57 observations this criterion is fulfilled. All calculations were carried out using SmartPLS version 2.0.M3, a statistical package developed for the estimation of SEMs using the PLS approach (Ringle et al. [2005]).

As proposed by Chin [1998a], evaluation of the structural equation model is done in two steps. First, the statistically measurable validity of the measurement model is tested. Thereafter, the structural model is evaluated. This procedure allows us to test Hypotheses 1, 2, and 3.

Furthermore we evaluate the mediation effect of the *Intensity of Information Sharing* variable (Hypothesis 4), i.e. whether the positive impact of *Vertical Forward Integration* on *Performance* can be explained by a higher degree of *Information Sharing* enabled by it. This mediation effect is tested based on the approach outlined by Baron and Kenny [1986] and has already been applied in multiple research works (e.g. Hassanein and Head [2007]). According to Baron and Kenny [1986], a variable mediates a relationship between two other variables when it fulfills the following criteria:

- there is a significant relationship between the independent variable and the presumed mediator (i.e., path VFI → IIS),
- there is a significant relationship between the mediator and the dependent variable (i.e., path IIS → PBM), and
- if the above mentioned paths (VFI → IIS and IIS → PBM) are controlled, a previously significant relation between the independent and dependent variables becomes insignificant.

We test the mediation effect of the IIS construct by estimating two models (based on the same data). In addition to Model A, we evaluate the alternative Model B with a direct causal link from the VFI construct to the PBM construct. The mediation effect exists if and only if the significant VFI → PBM path in Model B becomes insignificant once the mediator variable (IIS) is integrated into the model (Model A) (Baron and Kenny [1986], Hassanein and Head [2007]), assuming the other above-mentioned conditions are fulfilled.

5.4.4 Evaluation of the Measurement Model

According to the standard validation procedure, the evaluation of the measurement model comprises the evaluation of the convergent and discriminant validity. The criteria used to test the convergent validity are indicator reliability of the chosen items, composite reliability and average variance extracted (AVE) for each latent variable, and Cronbach's Alpha. In order to test Hypothesis 4, two models (Model A and Model B) are evaluated.

In order to assure indicator reliability, each latent variable should be accountable for at least 50 percent of the variance of the corresponding indicator. Thus, the loading of a latent variable on the individual indicator should return a value larger than 0.7 (Carmines and Zeller [1979], Hulland [1999]). 14 indicators fulfilled this requirement exceeding the threshold of 0.7. Three indicators with the loading values of 0.625 (VFI_3); 0.589 (VFI_5); 0.672 (PBM_6) have been removed during the model fitting phase. This practice is acceptable taking into account a large number of newly developed scales. Subsequent examination of the remaining items has shown that the essence of the constructs is still captured and thus content validity of the measured constructs can be assumed. Next, Cronbach's Alpha, a measure of internal consistency, for all constructs in both models (A and B) was assessed. As can be seen in Table 5.3, its values were higher than the required threshold of 0.7 for all latent constructs (Nunnally [1978]). In order to ensure composite reliability, its value should be higher than 0.6 for all constructs. Additionally, the AVE values of all constructs should to be at least 0.5 since otherwise the variance due to the measurement error would be higher than the variance captured by the corresponding construct (Fornell and Larcker [1981]). As can be seen in Table 5.3, the composite reliability and AVE thresholds were surpassed by all constructs. Since all criteria were fulfilled, convergent validity can be assumed.

Discriminant validity verifies the extent to which measures of distinct constructs differ (Bagozzi and Phillips [1982]). According to Fornell and Larcker [1981], discriminant validity is ensured when the AVE values for all latent variables stay greater than the squared correlation between the latent variable and any of the other latent variables in the same model. This criterion was ensured for all constructs as shown in Table 5.4.

	Latent Variable	Item	Mean	SD[a]	SFL[b]	AVE[c]	CR[d]	CA[e]
Model A	Vertical Forward Integration	VFI_1	4.34	1.20	0.743	0.64	0.84	0.72
		VFI_2	3.50	1.35	0.756			
		VFI_4	3.70	1.22	0.888			
	Intensity of Information Sharing	IIS_1	3.70	1.30	0.898	0.81	0.96	0.95
		IIS_2	3.94	1.34	0.904			
		IIS_3	3.83	1.28	0.862			
		IIS_4	3.94	1.25	0.921			
		IIS_5	3.72	1.20	0.917			
		IIS_6	3.70	1.22	0.910			
	Performance of the Brand Manufacturer	PBM_1	3.34	1.06	0.883	0.77	0.94	0.92
		PBM_2	3.49	1.02	0.899			
		PBM_3	3.48	0.87	0.819			
		PBM_4	3.52	1.08	0.860			
		PBM_5	3.57	0.98	0.914			
Model B	Vertical Forward Integration	VFI_1	4.34	1.20	0.757	0.64	0.84	0.72
		VFI_2	3.50	1.35	0.751			
		VFI_4	3.70	1.22	0.883			
	Performance of the Brand Manufacturer	PBM_1	3.34	1.06	0.882	0.76	0.94	0.92
		PBM_2	3.49	1.02	0.900			
		PBM_3	3.48	0.87	0.806			
		PBM_4	3.52	1.08	0.883			
		PBM_5	3.57	0.98	0.895			

[a]Standard deviation
[b]Standard factor loading
[c]Average variance extracted
[d]Composite reliability
[e]Cronbach's alpha

Table 5.3: Quality criteria of the constructs

5.4.5 Evaluation of the Structural Model and the Mediation Effect

In contrast to the covariance-based approach, no overall measures of goodness of fit are available when using PLS. The model validity in PLS can be assessed by examining the resulting R^2 values and the structural paths

Model A				Model B		
Construct	VFI	IIS	PBM	Construct	VFI	PBM
VFI	0.800			VFI	0.800	
IIS	0.367	0.900		PBM	0.232	0.872
PBM	0.219	0.516	0.877			

Table 5.4: Square root of AVE (diagonal elements) and correlations between latent variables (off-diagonal elements)

(Ringle [2004]). Evaluation results concerning the structural models (Models A and B) are presented in Table 5.5 and Figures 5.2 and 5.3.

The results of the PLS analysis show that 26.7% of the variance in the dependent variable (*Performance of the Brand Manufacturer*) is explained by the variables in the model. Recommendations for an acceptable level of R^2 start with 33% (Chin [1998b]). However, it is important to note that it was not our main focus to fully explain the factors behind the performance of the brand manufacturers. Instead, we concentrated our efforts on deepening the understanding of the dynamics between information sharing, vertical forward integration, and company performance. Taking into account that only two factors explained that much of a variance in the dependent variable tested in a novel context, the explanatory power of the model is high.

At the next step the values of the path coefficients and their significance

Hypothesis	Construct A → Construct B	Path Coefficient	P-value	Rejected/ Supported
Model A				
Hypothesis 1	IIS → PBM	0.503	5.171***	supported
Hypothesis 2	VFI → IIS	0.367	3.354***	supported
Hypothesis 3	VFI → PBM	0.035	0.315	rejected
Model B				
Hypothesis 4	VFI → PBM	0.232	2.145*	supported

***Significance at 0.1%; **Significance at 1%; *Significance at 5%

Table 5.5: Path coefficients, P-values and hypothesis evaluation

were evaluated for Models A and B. It is recommended that the values of the path coefficients exceed the 0.2 threshold (Ringle [2004]). For Model A we find that the path coefficient between *Vertical Forward Integration* and *Intensity of Information Sharing* (VFI → IIS) is high (0.367) and significant. Similarly, there exists a strong significant link (0.503) between *Intensity of Information Sharing* and the *Performance of the Brand Manufacturer* (IIS

→ PBO). Thus, Hypotheses 2 and 1 are supported. We find the link between *Vertical Forward Integration* and the *Performance of the Brand Manufacturer* to be insignificant for model A, which rejects Hypothesis 3. The evaluation of the Model B, when the IIS construct is removed, rendered a strong (0.232) and significant link between both constructs. The explained variance in the dependent variable (*Performance of the Brand Manufacturer*) constituted $R^2 = 5.4\%$. The comparison of Models A and B provides strong evidence that *Intensity of Information Sharing* is a dominant mediator in our conceptual model. Thus, Hypothesis 4 is confirmed.

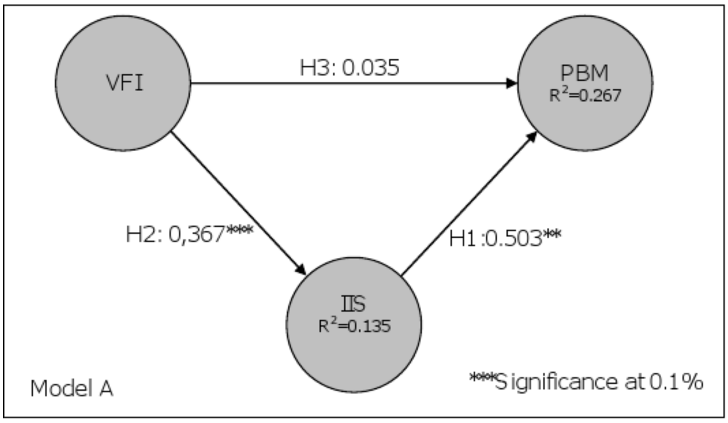


Figure 5.2: Evaluation results for Structural Equation Model A (PLS)

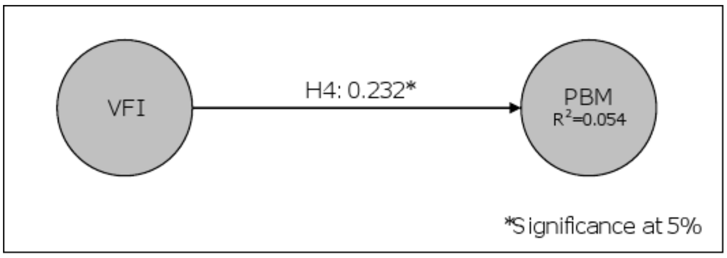


Figure 5.3: Evaluation results for Structural Equation Model B (PLS)

5.5 Conclusions and Managerial Implications

The statistical results show that vertical forward integration is not a sufficient condition for success in the fashion business: Hypothesis 3 was not supported by our data. However, our model shows that vertical integration does have an indirect impact on performance because it also enables profitable information sharing practices. Indeed, we find that the intensity of information sharing along the supply chain mediates the relationship between the vertical forward integration and the performance of brand manufacturers (Hypothesis 4). The importance of free information flow in the apparel supply chain is an important finding of our study: a high intensity of information sharing activities between the brand manufacturer and the retailers leads to increased performance of the brand manufacturer (Hypothesis 1). The high and significant path coefficient is an indication of the extremely high relevance of timely demand signals, particularly in the fashion business.

According to the evidence presented above, information sharing between manufacturing and retail and the improved coordination it enables are crucial for the performance of supply chains. Our results suggest that manufacturers who exert more control over the sales activities of the retailers manage to leverage the informational exchange with retailers better than those that are less integrated with retail. A possible explanation of this results is that more control helps to create the necessary incentives for information sharing in the first place. This could explain why the most vertically integrated companies, in particular fast fashion retailers like Zara, are the most successful in their respective market segment.

5.5.1 Implications for Brand Manufacturers

We have shown that exerting more control over the retail channel tends to improve the performance of brand manufacturers (albeit indirectly). A manufacturer should therefore try to obtain this kind of control. However, setting up their own retail operations may be too expensive and risky for many traditional brand manufacturers. Closer cooperation between brand manufacturers and existing retailers can be a viable alternative and preserve competitiveness while continuing to reap the benefits of the traditional division of tasks. As our results indicate, cooperation could be characterized by a moderate expansion of the manufacturer's decision rights with respect to sale activities combined with timely and reliable information sharing. When item-level RFID has been rolled out in apparel supply chain the implementation of information sharing practices will be easier since retailers can simply grant the manufacturers access to their RFID data and vice versa. Manufacturers pursuing a vertical integration strategy should be prepared to provide additional incentives to retailers: beyond sharing more data, they should be ready to redistribute a part of their gains among participating retailers; for example by contractually reducing their demand risk (cf. Cachon [2003]).

5.5.2 Implications for Retailers

Since we only measured the business performance of the brand manufacturers, the implications for retailers are less clear. Without doubt many traditional fashion retailers are currently struggling to survive. Sticking to the status quo and continuing with their current business model is hardly an option. Competitive pressure will not fade since market entry barriers in fashion retailing are low and consumer taste changes quickly. Retailers could now begin to create their own brands but that is expensive and risky. A viable middle course could be to favor contractual agreements, such as shop-in-shop, or concessions that transfer a part of their traditional decision rights regarding marketing and sales to the brand manufacturers. They may also want to share more of their proprietary information on sales trends and consumer taste with manufacturers, in order to deepen the business relationship with manufacturers and strengthen the entire supply chain. If they are already in the process of item-level RFID evaluation or even roll-out, they should consider the required processing of RFID data for enabling information sharing agreements with manufacturers. The RFID-based sharing of information about the location of items at certain times can be achieved by implementing the EPCIS standard proposed by EPCglobal and allowing the manufacturers to access EPCIS repositories. Knowing that information sharing agreements of the considered type lead to substantial gains for manufacturers, retailers should demand a fair share of the gains.

5.5.3 Limitations

Regarding the data and methodology we have used, there is a number of limitations which may affect the validity of our conclusions.
Similar to other survey-based research our study can be subject to a sample selection as well as a self-selection bias. The term sample selection bias refers to the way data is collected, especially with respect to the selection of respondents. The very fact that only a fraction of the German apparel industry could be included into the analysis implies that full representativeness cannot be assumed. However, the sample characteristics displayed in Table 5.1 do not reveal obvious concentrations of certain types of companies.
Self-selection refers to an overrepresentation of a particular type of respondent in the sample. Applied to our case, it might for instance be possible that managers who have been more successful in implementing a vertical integration strategy or advanced information sharing practices were more likely to

take part in the survey. The possible influence of self-selection on our results is hard to rule out.
A more specific limitation of our results is due to the possibility that survey participants subjectively implied a positive correlation between the intensity of information sharing and performance: if an apparel company has been doing well in the past, managers of that company may subjectively attribute this to better communication with the companies' points of sale and thus be more likely to give the related items a higher rating. To some degree this effect can be controlled by limiting the freedom regarding the interpretation of questions: the resulting bias contained in the data can be expected to be stronger the more leeway regarding the interpretation of the corresponding questions leave to survey respondents. Whereas the scales IIS_4-6 (see Table 5.2) are rather general and leave more room for subjective interpretation, IIS_1-3 explicitly refer to the exchange of concrete types of data items (e.g. POS data and sales schedules) which leaves far less room for subjective judgment. Furthermore, the company performance measures used in this study (PBM_1-5) refer to "hard" numbers like the ROI and leave relatively little room for interpretation. Thus, the possible bias in our data which is due to the respondents' subjectivity should not be significantly higher than in other survey-based studies. Certainly, collecting actual field data by visiting companies and objectively observing their practices would be more accurate. However, in order to obtain a sufficient sample size such an approach was not followed due to resource limitations.

5.5.4 Outlook

The question remains whether more centralized control of the supply chain is the only way to leverage common information. Although our results suggest that vertical forward integration represents one possible way to pursue this goal, the creation of trust or the use of contracting schemes that do not dictate the reassignment of decision rights could also create incentives for profitable information sharing. Numerous authors have suggested that supply chain performance can be improved by "collaboration" (cf. e.g. Simatupang and Sridharan [2002]), i.e. by coordinating supply chain control and execution without compromising the full autonomy of the supply chain participants. The future will tell whether the concept of supply chain collaboration is a viable alternative to prudent vertical integration strategies. What is clear is that information sharing remains a crucial practice to make either approach work. As far as the monitoring of product flows in the supply chain and within the stores is concerned, the availability of semantically enriched RFID data (e.g. EPCIS events) could significantly contribute to the success of supply chain coordination.

Chapter 6

Conclusions

Although the adoption of Radio Frequency Identification (RFID) is slowly gaining pace, its main supporters on the provider as well as on the user side are dissatisfied with the speed of its introduction. Previous research has identified that this is due to at least two reasons: (i) RFID is still no "plug and play" technology meaning that its technical integration into the IT landscape of companies and supply chains remains a significant challenge. Although the recent years has brought major progress in the area of standardization and product development, the slow adoption of the technology in practice still prevents RFID from reaching full technological maturity. (ii) The value of RFID, especially if it is used for monitoring the movement of products in supply chains, is still disputed in practice. The obvious advantages of RFID over the bar code are perceived as too insignificant by many companies to justify the current hardware and integration cost.
We believe that the adoption of RFID has reached a critical state. It can only proceed if companies begin to tag products on the item-level and integrate the technology in as many processes as possible along the supply chain. This would lead to a sharp decrease of hardware and integration cost on the one hand and will help to reveal its true potential which, as we and others have shown, by far transcends time and labor cost savings. However, to date there are only very few companies that have begun to deploy item-level RFID. Although their experiences with the technology are positive, the large majority of potential users still shies away from introducing it on a large scale. What seems clear is that item-level tagging will most likely be deployed first in environments where it provides the highest value and will then make its way into more and more processes, companies, and industries. Currently a number of apparel companies leads the field of early item-level RFID adopters, presumably because of a unique combination of typical operational challenges and product characteristics that favor the use of RFID in

this industry. Our results support this view. It remains to be seen whether RFID will penetrate this industry and move on to another one with where its potential is rather high, e.g. the consumer electronics or pharmaceuticals industry.

This dissertation has focused on RFID's information and transformation value as well as the strategic implications of its use in the supply chain of what we have called "high-impact" consumer products such as apparel and consumer electronics. Using both economic modeling and empirical analysis we have provided insights into why and under what circumstances item-level RFID is profitable. In each chapter we have investigated the RFID value proposition from a different angle.
Chapter 2 has focused on its value for different supply chain participants. We have identified a number of economic externalities resulting from RFID usage which will contribute to its cooperative use along the supply chain once the retailers request products to be tagged. This result is good news for IT providers who plan to offer applications based on RFID data that has to be collected at several stages of the supply chain.
Chapter 3 has investigated RFID's information value in retail stores. We have revealed the different factors influencing the ROI of item-level RFID in typical retail stores and have shown that it is positive even under conservative assumptions.
The results of Chapter 4 has underlined the potential of item-level transshipments that could be enabled by item-level RFID. We have demonstrated that even if the regular order policy is optimal and the full tagging cost is subtracted from the benefit they provide, transshipments can significantly increase profits.
Chapter 5 investigated the role of information sharing in the context of vertical forward integration. Our empirical results suggest that its importance should not be underestimated by brand manufacturers wishing to increase their control over the sales channel. Item-level RFID could enable certain information sharing practices helping to make vertical forward integration a success. The industry consortium EPCglobal has defined an architectural framework that has the potential to provide manufacturers with a standardized way to access reliable real-time information about the way each of their products are handled and sold to the end-consumer. This possibility could in fact revolutionize the retail supply chain in the long term.

RFID's appeal to researchers and practitioners will remain high. Especially the interconnection and global standardization of RFID infrastructures paves the way for innovative information services. This "Internet of Things" represents a basic IT infrastructure that can be used by existing applications, e.g. from the supply chain area, or completely new applications that we can only speculate about at this time.

The two main areas that have been addressed by researchers in the past should stay in the focus of the information systems community: its business value in various applications and its technical advancement. There remain many promising applications of RFID to be evaluated in terms of economic value and feasibility. More extensive empirical research based on data obtained from early RFID adopters could provide useful insights into the RFID value creation process and how it can be geared and accelerated. On the technological side of things, two aspects deserve more attention: the "plug-and-play" capabilities of RFID infrastructures in standard enterprise settings and the farsighted design of the networking infrastructure that is supposed to enable the efficient, reliable and secure retrieval of object-related data.

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Selbständigkeitserklärung

Ich bezeuge durch meine Unterschrift, dass meine Angaben über die bei der Abfassung meiner Dissertation benutzten Hilfsmittel, über die mir zuteil gewordene Hilfe sowie über frühere Begutachtungen meiner Dissertation in jeder Hinsicht der Wahrheit entsprechen.